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THE UNIVERSITY OF ALBERTA

"CLEAVAGE AND RELATED STRUCTURES IN PRECAMBRIAN  
ROCKS NEAR JASPER, ALBERTA"

by



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A THESIS

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The undersigned certify that they have read,  
and recommend to the Faculty of Graduate Studies  
for acceptance, a thesis entitled "Cleavage and  
Related Structures in Precambrian Rocks Near Jasper,  
Alberta", submitted by John William Zaturecky, B.Sc.,  
in partial fulfilment of the requirements for the  
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## ABSTRACT

Local and regionally penetrative microscopic and mesoscopic structures in the folded, faulted and regionally metamorphosed rocks of the Precambrian Miette Group lying in the Pyramid Thrust sheet near Jasper, Alberta, have been examined in detail. These structures, including cleavage and other features related to folding, record a sequence of penetrative re-adjustments undergone by Miette Group rocks during a single period of deformation.

Five mesoscopically and microscopically distinguishable types of cleavage, together with their principal sub-types and gradations between them were studied throughout the area, and are described here in terms of their geometry and appearance, both in outcrop and thin-section. Geometrically, the five major types include both cleavages parallel to (Cleavages A,C,E,) and inclined to the axial surfaces of folds (Cleavages B,D,E,). Three of these cleavages (A,B,D,) possess two partial sub-fabrics: the mica-rich zones through which the planes of mesoscopic parting pass, and less micaceous inter-cleavage domains in which a dimensional alignment of mineral particles is generally prominent. Cleavages C and E are associated with prominent displacements parallel to the cleavage planes.

Detailed structural analysis was carried out on a simple fold in which three of the above cleavage types, abundant quartz deformation lamellae and a host of other structures are displayed to advantage.



Post-cleavage shearing along cleavage surfaces in the axial plane types has produced: 1) micro-folded bedding in slates, limestones and siltstones; 2) kink folds and flexured cleavage domains in slates; 3) Cleavage mullions in limestones and slates, and cleavage boudinage in siltstones; and 4) oblique shearing or cross-fracturing in slates. The development of inclined cleavages was accompanied by internal rotation of detrital grains and older structures, and by external rotation due to folding. Recrystallization played but an insignificant role in the development of the deformation fabric.

The presence of abundant deformation lamellae in quartz grains of the conglomeratic lower Wynd sandstones suggests that these rocks behaved plastically early in the folding history.

Internal re-adjustment of the original fabric of these rocks is, therefore, presumed to have been accomplished by internal particle rotation, plastic flow or glide, flexuring and shearing. These re-adjustments are believed to have taken place under conditions of high pressure in a gently plunging regional stress system. Local variations in deformation fabric probably reflect variations in the intrinsic properties of the materials during deformation, as well as local stress deviations.



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## INTRODUCTION

Structurally, the Canadian Rocky Mountains rank among the most thoroughly investigated and best known ranges of the so-called Alpine type. Yet, relatively little thought or effort has thus far been expended on structural analysis at the mesoscopic and microscopic levels. For that reason, most existing tectonic syntheses should be considered incomplete.

Attractive possibilities for both microscopic and mesoscopic investigation are provided by the coarse-to-fine clastics of the Precambrian Miette Group near Jasper, where several styles of folding are well displayed. Low-grade regional metamorphism accompanied the single period of deformation responsible for most of the structures in the Miette Group, so the folds are associated with several other structures, notably cleavage. Since Miette Group rocks are neither extensively metamorphosed nor multiply deformed, they may reasonably be expected to contain evidence of the mechanics of deformation on a smaller scale than has been previously attempted.

Accordingly, this study, initiated near the end of the 1966 field season, has set out to:

- a) describe various mesoscopic and microscopic structures in the Jasper area, with a view toward classifying them according to form, orientation, habitat and origin;
- b) correlate microscopic, mesoscopic and macroscopic



structures;

- c) add to what is already known about the kinematics and dynamics of deformation within the area.

## FABRIC ANALYSIS: DEFINITION AND PRINCIPLES

A geological body may be defined as a volume of rock of any size, with or without natural bounding surfaces; its size may range from that of a crystal to that of a continent or ocean. The structure of a geological body is best described in terms of the nature and orientation of identifiable structures contained by the body. These structures, which are either surfaces or lines, exhibit a range in size similar to that exhibited by geological bodies. The structure of a geological body is usually the result of a long sequence of events. For example, that of a deformed sedimentary body is the net result of a series of cumulative changes which include the effects of deposition, compaction, diagenesis and deformation.

A geological body can be said to be homogeneous on a certain scale when the structure of any volume element is the same as that of all other volume elements with dimensions equal to or larger than the scale under consideration. Homogeneity associated with one structure may not apply to other structures present. Structural geologists commonly refer to homogeneous geological bodies as domains. A structure homogeneously distributed within a domain is said to be penetrative, and may be called a fabric element;



fabric elements describe the fabric of a domain. Fabric is either isotropic or anisotropic depending on whether the fabric element shows a random or a preferred orientation, respectively. Fabric is studied by the technique known as structural analysis.

### Structural Analysis

Structural analysis involves both the determination of the structure of a body and an interpretation of the origin of the structure. The descriptive phase of structural analysis includes the identification of the structures present and the measurement of their orientation, shape, and size. The interpretative phase includes the elucidation of both the movements which produced the existing configuration of structures (kinematic analysis), and the orientation, nature and origin of the stresses and causative forces responsible for these movements (dynamic analysis).

During the first phase of structural analysis the class and scale of structures to be studied are chosen. Generally structural analysis concerns itself not so much with features which are in a genetic sense primary (i.e., constructional), as it does with secondary (or imposed) features resulting from deformation and composite features resulting from interplay of deformational upon primary features. The scale of the body determines the particular technique of investigation which will be applied to it. Scale also controls the type of structure to be studied: for example, the structural



analysis of an entire mountain range is unlikely to include an examination of the optic axes of quartz grains whereas detailed analysis of a small fold in quartzite probably would. Structural petrology is merely structural analysis of geological bodies that range in size from sub-microscopic to mesoscopic and which, by definition, can be examined virtually in their entirety. The recognition of structures within such bodies together with their measurement is known as petrofabric analysis.

### Fabric Symmetry

Bruno Sander originally proposed that the fabric symmetry of a deformed rock reflects the kinematic symmetry of its deformation (Paterson and Weiss, 1961; den Tex, in Hills, 1963). This proposal implies a 'cause' and 'effect' relationship between symmetry of the movements which produced the present fabric of the deformed rock and the symmetry of the fabric elements. Symmetry arguments are framed in terms analogous to the systematic classification used in crystallography. A carefully constructed diagram of the geometry of fabric is considered by most investigators to be a more accurate reflection of the kinematics of deformation than the best theoretical strain model which can be designed intuitively.



## SCALE, SYMMETRY AND SIGNIFICANCE OF CERTAIN STRUCTURES

In the following discussion of modern ideas concerning the nature and origin of certain geological structures emphasis has been placed on the more controversial issues. These structures are considered in turn according to the scale on which they occur.

### Fabric Scale

Sander's procedure for fabric analysis requires subdivision of the body under investigation into domains of similar scale. The total fabric of any domain is generally comprised of numerous sub-fabrics, each corresponding to some fabric element. The fabric defined by each of these individual elements, when combined with other sub-fabrics, defines the fabric of the deformed body. Sub-fabrics may have the same symmetry as, or a higher symmetry than the total fabric. When fabrics share a common symmetry they are said to be homotactic, but if the fabrics are discordant they are called heterotactic. The sub-fabrics of most deformed rocks are heterotactic, although certain combinations of sub-fabric may be homotactic.

### Microscopic Fabric

Microscopic fabric domains, such as might be contained in a single thin-section or polished surface, can be conveniently examined in their entirety using the microscope,



X-ray diffractometer and electron microscope. Due to its abundance in metamorphic rocks and the relative facility with which its optical orientation and deformational features can be measured microscopically, the sub-fabric of quartz is probably the most extensively studied of all microscopic sub-fabrics in naturally deformed rocks. Naturally deformed quartz is characterized by deformation lamellae, undulatory extinction and, less commonly, kink bands (Figure 1). These features, now believed to be evidence of plastic deformation in quartz, have all been reproduced in the laboratory using several types of apparatus.

#### Deformation Lamellae

Deformation lamellae in both naturally and experimentally deformed quartz are thin, parallel, sub-planar lenses and layers which pervade part or all of a grain with nearly constant orientation. Lamellae are visible both in plane-polarized light and under crossed polarizers. When in focus in plane-polarized light they are brighter than the host material. They have sharp boundaries and are asymmetric such that one side of the discontinuity appears to be brighter than the other. The dark side has higher refractive indices and birefringence than the host crystal on that side, while the light side shows correspondingly lower indices and birefringence than the host quartz on that side. Some natural lamellae differ from those experimentally produced in that

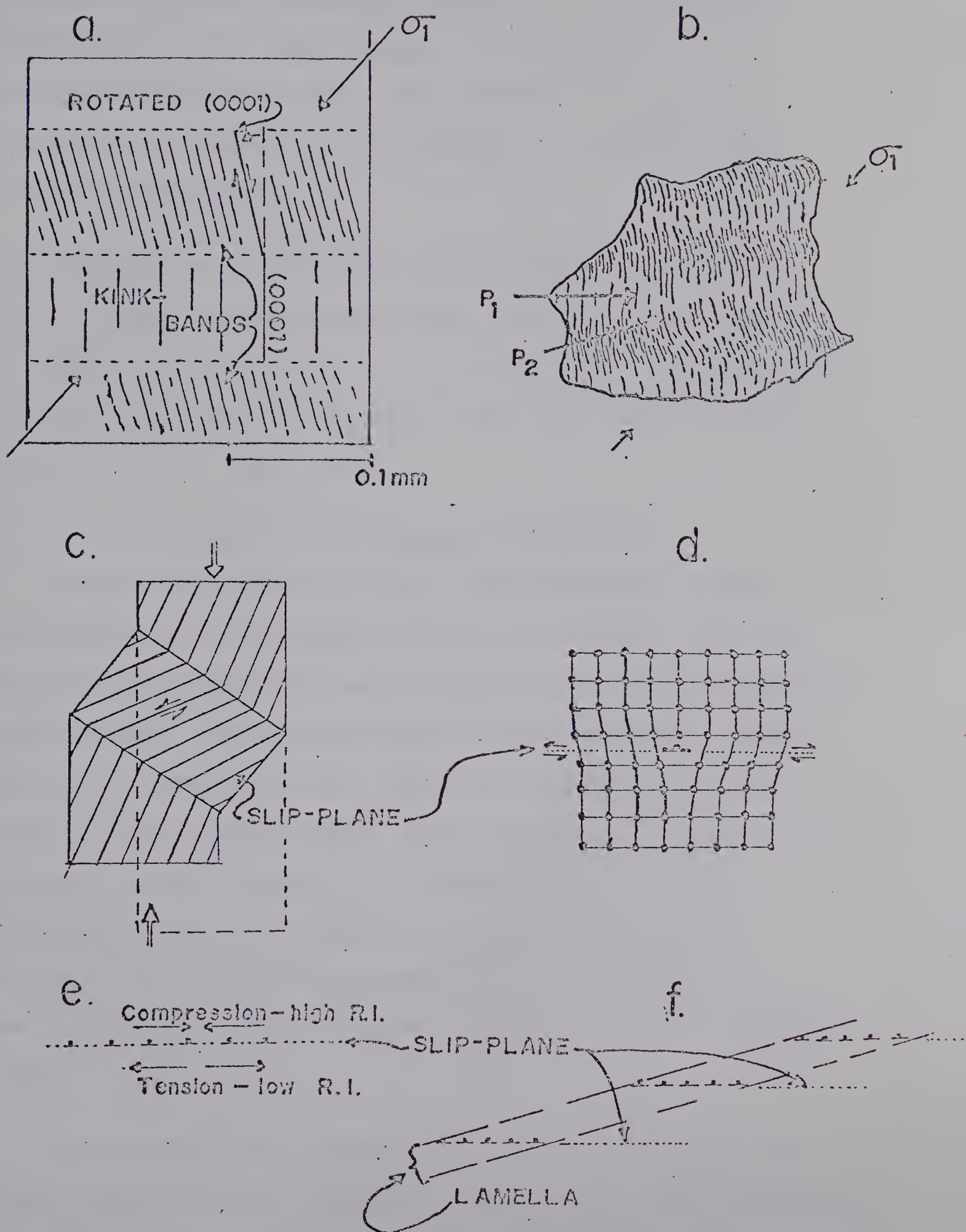


Figure 1 Deformation structures in quartz (after Carter and Friedman, 1965; Christie et al, 1964).

- a Horizontal kink bands (east-west zones) in an experimentally deformed quartz crystal, steeply dipping basal deformation lamellae appear as well developed linear features which, in the kink bands, have been externally rotated by localized slip. The applied maximum principal stress axis ( $\sigma_1$ ) was so oriented initially that the shearing stress on the basal (0001) plane was high.
- b Experimentally produced undulatory extinction in a deformed quartzie grain. The deformation lamellae are more closely spaced in the regions where the crystallographic c-axis has been rotated toward  $\sigma_1$ . The poles to these lamellae ( $P_2$ ) have also been rotated toward  $\sigma_1$ .
- c Sketch of kink band developed sub-parallel to the quartz c-axis by slip along a near basal glide system; movement was contained in the plane of the diagram. Deformation of the compressed single crystal is restricted to the band.
- d Main components in the stress field of an edge dislocation in a simple lattice. The lattice is in compression on the side with the extra half-plane, and in tension on the other; the shear stresses on the slip plane have the senses indicated.
- e Array of parallel edge dislocations locked in a slip plane. The stress components shown result in a difference in the refractive indices (R.I.) across the plane.
- f Simple model for deformation lamellae which are not parallel to the slip plane but give optical effects similar to those in le. In this case the lamella shown is a band of finite thickness which has been either externally rotated by en echelon slip within the bands, or has been bodily rotated (internal rotation) by slip on some system inclined to the lamella.



FIGURE 1





they are not sharp and clear but contain microscopic to sub-microscopic brownish inclusions; these are informally called 'decorated' lamellae. Such granular-looking inclusions were present in the lamellae first described by Bohm in 1883. The presence or absence of decoration is believed to be largely a function of the rate of deformation.

Most lamellae are inclined at  $10^{\circ}$  to  $30^{\circ}$  to the basal (0001) plane in naturally deformed quartz, though lamellae at higher angles to (0001) are not uncommon. Experimentally produced lamellae, on the other hand, are found at less than  $12^{\circ}$  to the basal plane.

#### Kink-bands and Undulatory Extinction

Both undulatory extinction and kink-bands involve reorientation of the quartz lattice by bending. The two features are similar in most respects but some investigators differentiate them on the basis of the radius of bending of the basal plane along the boundaries between reoriented zones (Carter et al, 1964); if the radius of curvature of bending is small compared to the half-width of the reoriented zone, the feature is called a kink-band. However, the distinction between the two features is purely arbitrary since there is complete gradation between them.

Kink-bands are generally less than 0.05 mm wide and occur parallel to one another forming a set which terminates within a grain or at a grain boundary; bands may also occur



singly or as minor, locally developed sets intersecting the main set at nearly right angles. When kink-band boundaries are sharply defined they can be treated as planar structures; however, most kink-bands in naturally deformed quartz have boundaries too diffuse for accurate measurement. Poles to experimentally formed kink-bands generally define two maxima roughly at 45 degrees to the maximum principal stress axis ( $\sigma_1$ ), indicating that the bands formed in planes of high shear stress. Since these kink-bands tend to form only in grains and crystals so oriented that shear stress on (0001) is high, Christie et al (1964) conclude that the kink-bands sub-parallel to the c-axis result from basal slip and kinking of the slip planes (Figure 1c). They suggest that temperature and rate of deformation may be the determining factors between sharp and diffuse boundaries in kink-bands, the slower strain rates in natural deformations accounting for the scarcity of kink-bands in naturally deformed quartz (op. cit., pp. 743,748).

As a rule, deformation lamellae occur approximately perpendicular to the boundaries of both kink-bands and undulatory extinction zones, though lamellae may change orientation in the vicinity of the boundaries themselves, and become closer spaced (Figure 1a, b).



## Origin of Deformation Lamellae

Experiments on single crystals of quartz at high confining pressure with high shear stress on the basal plane have produced deformation lamellae oriented sub-parallel to the basal plane and nearly normal to the extinction bands (kink-bands and undulatory extinction) which develop in zones sub-parallel to the c-axis. The lamellae and extinction bands are believed to be produced by translation gliding on the basal plane, and by kinking and bending of the slip planes (Christie et al, 1964). The experimental lamellae are probably optically visible traces of slip due to photoelastic effects resulting from stresses set up by dislocations along slip planes. Natural lamellae are thought to lie at higher angles to (0001) either because they have been internally rotated by localized slip on systems inclined to the basal plane, or because some of the lamellae formed in thin bands by en echelon arrays of basal dislocations (Figure 1f). Quartz has seven completely identified slip systems in addition to basal slip, plus at least two other undetermined slip directions (Christie et al, 1966, p. 369). The desired slip system can be induced in single crystals by applying stresses so oriented that only the required plane is likely to be activated. Although slip can be induced from any of fifteen orientations, experiments on both polycrystalline aggregates with random



orientations and on single crystals suggest that the critical shear stress is lowest for slip on the basal plane parallel to an a-crystallographic axis (Carter et al, 1964; Carter and Friedman, 1965, p. 757).

### Geological Significance of Quartz Deformation

Since all three of the structures discussed above develop in grains so oriented that the basal plane is a plane of high shear stress, it should be possible for an investigator to draw some inferences regarding the probable orientation of the principal stresses which acted during deformation. A comparison of fabric diagrams generally shows that the preferred orientation of deformation lamellae is much stronger than that of quartz axes from the same domain. The typical fabric of natural lamellae has what approximates orthorhombic symmetry, usually exhibiting either strong paired maxima or a small circle girdle subtending an angle of 60 to 80 degrees. A clear correlation between lamellae fabric and that of mesoscopic foliations or lineations, or the optic axes of quartz is not always possible. However, in the case of the latter, correlation is generally fairly strong if only the optic axes of grains containing lamellae are counted.

Carter et al (1964) discussed possible relations between lamellae fabric and causative stresses in rocks containing quartz which initially had a random fabric:



- 1) under compression ( $\sigma_1 > \sigma_2 = \sigma_3$ ) the poles to lamellae should plot as a small circle girdle approximately 45 degrees from the  $\sigma_1$  axis;
- 2) under uniform extension ( $\sigma_1 = \sigma_2 > \sigma_3$ ) a similar small circle girdle should form about the least principal stress axis,  $\sigma_3$ .
- 3) in the more general case where ( $\sigma_1 > \sigma_2 > \sigma_3$ ) the strongest concentrations should form about 45 degrees from  $\sigma_1$  in the  $\sigma_1$ - $\sigma_3$  plane.

Departures from these ideal orientations are believed to be a function of original anisotropy and of the relative magnitudes of the principal stresses together with their respective orientation relative to the original fabric.

Carter et al (1964) have suggested on qualitative grounds that the changes in grain shape resulting from plastic deformation would be very small where the lamellae formed by en echelon arrays of basal dislocations but if the internal rotation mechanism predominates a rather large change in grain shape might reasonably be expected. These investigators go on to suggest that from their own experience there seems to be little correlation between grain shape and the inclination of lamellae to (0001). They also calculated that either mechanism would be unlikely to cause much change in the c-axis fabric of deformed aggregates.

In view of the above suggestions it is clear that there is considerable ambiguity involved in interpretation of



lamellae diagrams. Does a small circle axis represent the orientation of  $\sigma_1$ , for example, or does it represent  $\sigma_3$ ? What are the two equivalent axes in a double maximum pattern? What are the effects of variations from the ideal stress relations given earlier?

In some cases it is, of course, possible to infer which is the position of  $\sigma_1$  on the basis of external evidence. For example, take the solution of this problem in the case of a simple monogenetic fold. Planes of maximum shearing stress occur at 45 degrees to the greatest and least principal stress axes, and lamellae would tend to form preferentially in grains whose basal plane is a plane of high shear stress; we may assume that the lamellae developed at some stage of the folding during which the folded layer brought the basal planes of lamella-bearing grains approximately into one of the high shear positions. In the type of fold specified, the intersection of the mean lamellae planes should approximately parallel  $\sigma_2$ , and the angles between the two mean planes would be bisected by  $\sigma_1$  and  $\sigma_3$ . On these assumptions a fold model can be developed showing the configuration of the folded layer at the time of lamellae formation; from this, the principal stress orientations and, possibly, the relative magnitudes of the principal stresses can be inferred.



## Mesosopic Fabric

Mesosopic analysis deals with microscopic structures which are fabric elements on a mesoscopic scale as well as with mesoscopic structures. Mesoscopic structures are treated geometrically as planes (e.g. foliations), lines, (e.g. lineations) or as combinations of the two (e.g., folds). Statistical analysis is not given a very prominent place in the study of such features, and many mesoscopic analyses are wholly descriptive. Whether statistically treated or not, the orientation data collected in the field on the macroscopic scale, taken together with microscopic data, can be combined with mesoscopic descriptions to define the regional fabric.

### Lineations

Although lineation, as defined by Cloos (1946), can refer to any linear structure in or on a rock on any scale from microscopic to regional, fabric studies exclude any lineation which is not penetrative on the scale of the investigation. Lineations include linear features on planar structures (slickensides, mineral streaking), features due to the intersection of planar features (bedding/cleavage intersections), fold axes and mullions.

### Foliations

One of the commonest planar deformation structures



is the class of S-surfaces referred to as rock cleavage. Cleavage nomenclature is rather confusing since structural geologists have not yet agreed upon either terminology or mechanical significance of the phenomenon.

Several systems of classification have been proposed, three of which will be reviewed here:

- 1) geometric classification, based on the geometric relationship of foliation to larger-scale structures such as bedding and axial surfaces of folds;
- 2) morphological classification, based on the nature of the cleavage surface;
- 3) genetic classification, based on the inferred mode of origin.

Geometric Classification: As outlined here, the classification is largely a summary of Badgley's version (1965) of Knill's (1960) proposal.

Axial-Plane Cleavage: A single set of planar S-surfaces lies parallel to the axial planes of the folds in the district. A penetrative regional cleavage of this type thus defines the axial surfaces of the major folding and is useful for mapping fold axes and the working out of the details of fold structure.



Bedding-Plane Cleavage: A single set of planar S-surfaces lies parallel to the original bedding or to the compositional banding of an area.

Inclined Cleavage: Either a single set or two or more sets of S-surfaces inclined to both the bedding and to the axial planes of folds may be present. When two or more sets are present they may or may not be symmetrically disposed about the axial planes of folds.

Discussion: This geometric classification is similar to the classification of folds according to symmetry of profile and, for descriptive purposes, it is quite useful. By this system, however, it is possible for the type of foliation usually referred to as slaty- or flow-cleavage to fall into all three categories in a single region, a situation which some workers find distressing. Major difficulties include: a) an often encountered gradation of sub-regional slaty cleavage of the axial-plane type into a fanned (inclined) type elsewhere in the district; b) a parallel close- or wide-spaced 'fracture' cleavage in coarser-grained units which parallels axial surfaces of folds but is confined strictly to the axial regions of folds; that is, it is not a regionally penetrative axial plane cleavage as the classification suggests; c) There is no provision for 'curved' cleavages of either



the 'refracted' or 'bent' types.

Foliations and their mutual intersections either with each other or with bedding are often the basis for the assignment of mesoscopic fabric axes. For this reason some type of geometric classification is a necessity.

Morphological Classification: This classification is modified from Badgley's classification of cleavage as related to internal fabric, though Badgley differentiates them according to the nature of the S-surface rather than by internal structure.

Cleavage due to the parallel orientation of planar minerals: Cleavage surfaces are independent of the original bedding which appears to have been a passive surface during cleavage development. Generally, though not invariably, such cleavages are systematically oriented relative to the axial planes of associated folds. It is uncertain whether the mineral orientation is due to 'plastic' flow and/or shearing, or to static recrystallization under a stress field (see below).

Cleavage due to closely spaced fracturing: S-surfaces are fracture surfaces and are independent of any parallel arrangement of the mineral constituents of the rock which is cut. Such surfaces may become channels along which solutions may travel, or they may provide sites for later crystallization.



Crenulated or 'bent' Cleavages: Discrete S-surfaces separate laminar or lenticular domains, apparently as the result of flexuring of an earlier S-surface. Platy minerals in the deformed domains are generally brought toward parallelism with the new planes.

Discussion: Types 1) and 3) are often gradational within a single domain. Alternatively rocks with types 1) and 3) may be interbedded with units showing a type 2) cleavage. In graded beds type 3) grades into type 1) in the same rock unit.

Proposal: Composite Descriptive Classification: Knill has discussed geometric relations of cleavage types found in the Craginsh District of the Scottish Highlands (Knill, 1960). His major premises are:

- a) (the three morphological types of)...cleavage are distinct cleavage phenomena which under certain circumstances may grade into one another;
  - b) cleavage may develop either as an axial plane structure closely associated with the formation of folds, or as two or more sets inclined to one another and to the fold axial planes.
- (Knill, 1960, p. 322)

Similar opinions have been voiced by investigators familiar with other areas. The major objections to the use of Knill's classification as a universal system are largely founded on his genetically-oriented terminology, and there seems to be no serious objection to expressing cleavage attitude in terms of folded surfaces. Table I is a slightly modified version of Knill's summary of



cleavage relations in the Craginsh District which could serve as a provisional classification. Considerations of scale are important, and the present scheme was designed primarily for mesoscopic use.

TABLE 1 - PROPOSED COMPOSITE CLASSIFICATION  
OF CLEAVAGE (after Knill, 1960)

N A T U R E    O F S- S U R F A C E		G E O M E T R Y One set of S- surfaces //to axial surface		One or more sets inclined to axial surface and each other
CLEAVAGE INDEPENDENT OF PRE-EXISTING S-SURFACES	Cleavage independent of planar preferred orientation of mineral grains Consists of ruptural breaks or cracks at 1 mm to 1 inch spacing.	F R A C T U R E		
	Cleavage defined by planar preferred orientation of inequant minerals Less than 1 mm to several mm spacing	C L E A V A G E		
CLEAVAGE DEPENDENT UPON PRE-EXISTING S-SURFACES	Cleavage associated with crenulation of pre-existing S-surfaces From mm to inches in spacing	S L A T Y		
		C L E A V A G E		
		C R E N U L A T I O N		
		C L E A V A G E		



Treatment of Orientation Data: A graphical system has been devised to permit expressing of the orientation of cleavage in terms of the axial surfaces of related folds. The technique will be outlined briefly in terms of idealized orientation models (Figures 2 and 3).

The dashed horizontal line in Figure 2a represents the upright axial surface of an erect fold. If foliation, everywhere normal to bedding, was plotted on this graph all points would fall on the bedding-normal curve. However, if the upwardly fanned foliation anywhere enclosed an angle other than 90 degrees with bedding then the points would plot in the area between the bedding-normal curve and the plot of the axial surface. Normally, a curve drawn through a population of points falling between these two curves crosses the bedding-normal curve where the latter intersects the axial-surface line, as well as where the limbs become vertical prior to overturning.

Figure 2b was constructed using dip of bedding and the acute bedding/cleavage angle for an axial-plane cleavage as the coordinates. Superimposed on this figure is a symmetrical curve representing the axial-surface of an upright fold, also plotted in terms of the acute angle included between itself and bedding. An ideal axial-plane cleavage would plot along this curve. If the fold inclines instead of standing upright, then the axial-surface curve will be shifted to the right or left by an angular distance equal to the complement of the dip of the axial surface as measured along the



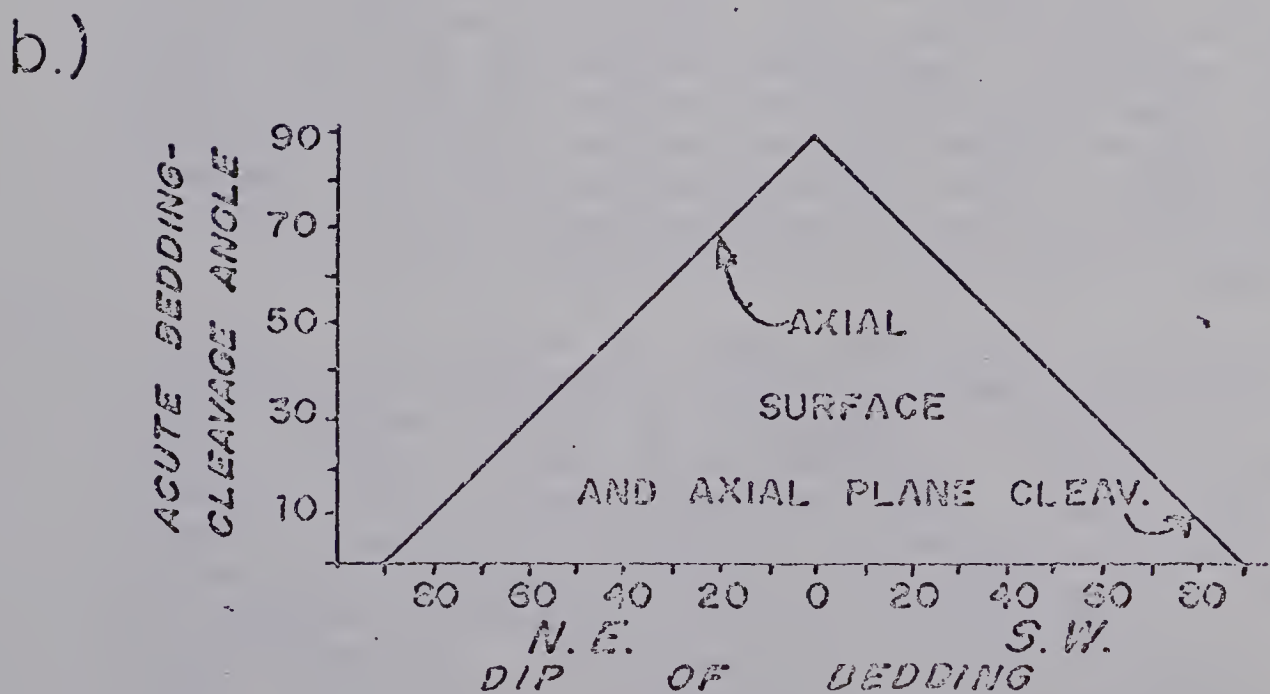
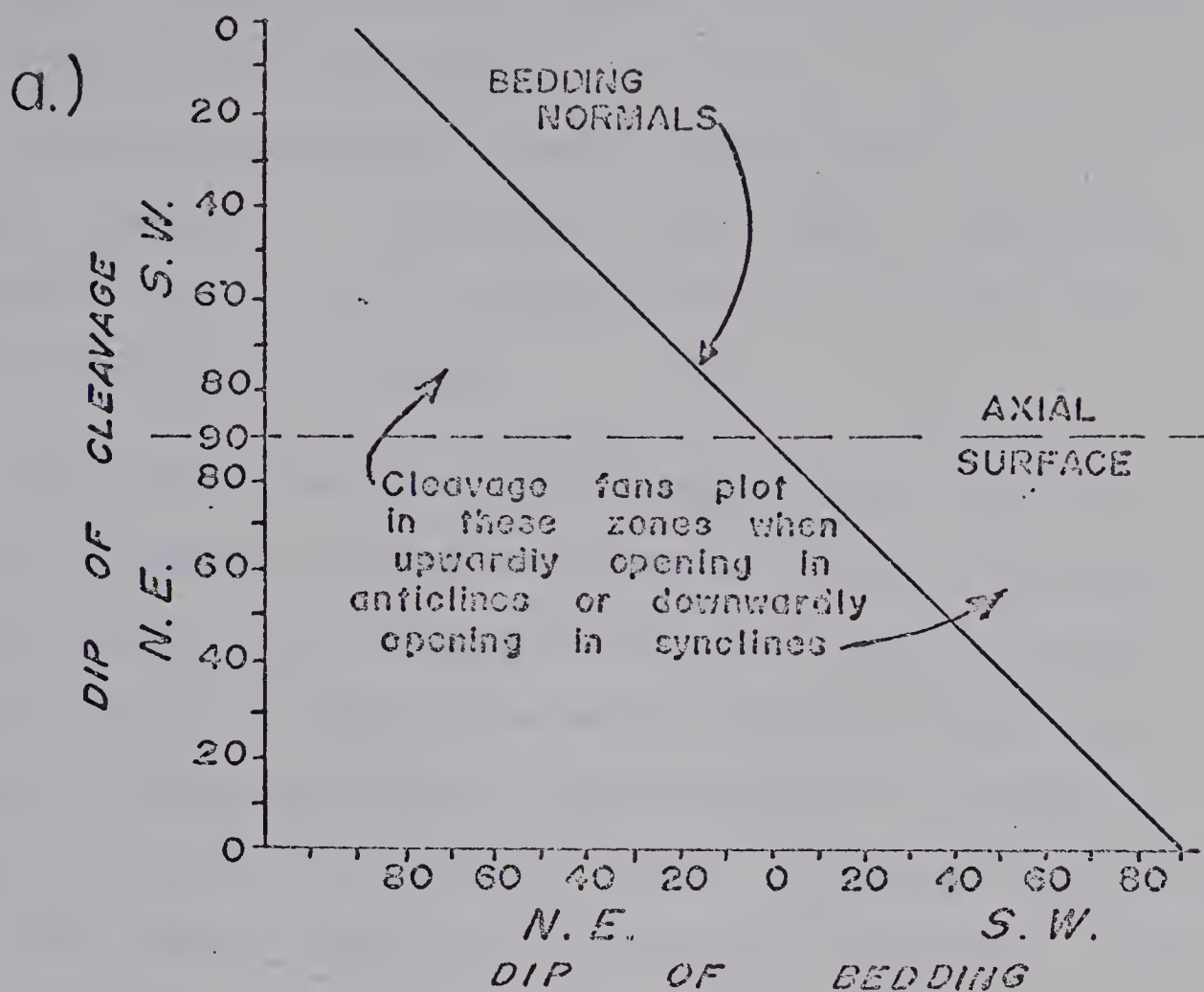


FIGURE 2: Relations between cleavage, bedding and fold elements in an upright anticline.



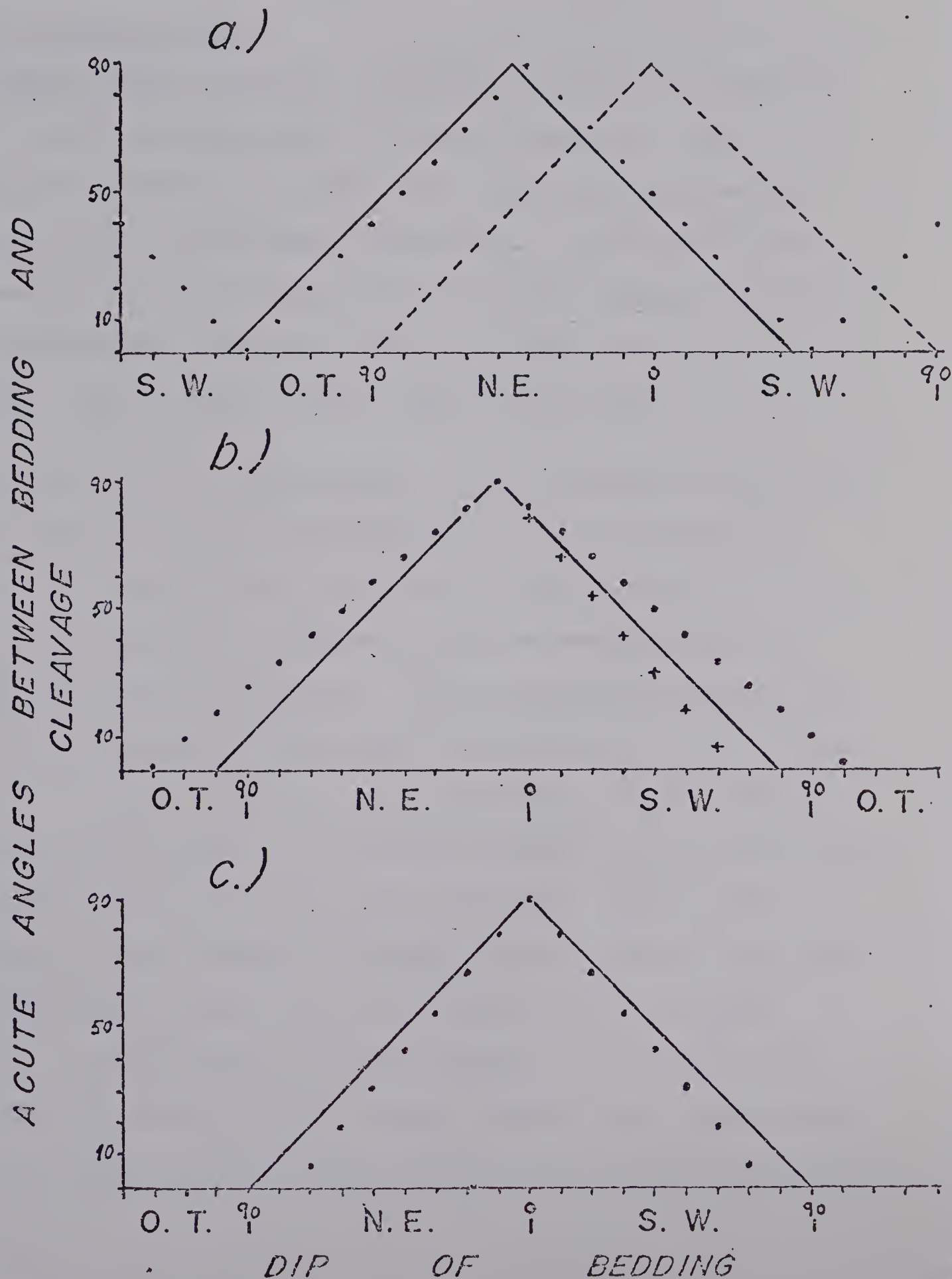
abscissa. Where the axial surface can only be estimated, for example where the behavior of cleavage across an anticlinorium is studied, a zone may be plotted instead (e.g., Figure 6). On a graph of the type in Figure 2b, cleavages about normal to bedding will, of course, plot across the top of the graph.

Among the advantages of the type of plot shown in Figure 2b are its ability to emphasize angular relations between bedding and cleavage in opposite limbs of folds, and its not yet fully explored potential for producing linear curves in situations where a type 2a curve is incapable of giving a curve with a constant slope. Figure 3 illustrates how a few simple cases may be interpreted using the second type of plot:

- 1) Cleavage has a constant orientation: Figure 3a illustrates a regional cleavage dipping 50 degrees southwest; cleavage is unrelated to the axial surface shown as a dashed line on the right, but nearly coincides with the axial surface at the left which inclines 45 degrees southwest. Because the slopes of both the acute bedding/cleavage angle and the bedding/axial surface angle curves are the same, cleavage does not vary around the fold. When the situation illustrated pertains to an anticlinorium, one is obviously dealing with a regional cleavage.
- 2) Cleavage fans about the axial surface(s): Figure 3b illustrates an upwardly fanned cleavage (shown by ...), which changes in dip by 2 degrees for every 10 degree change in the dip of bedding. The curve is flatter than the axial surface curve because the surfaces incline in opposite directions and the acute angle therefore equals the difference between the angular increment for each surface over a given interval. For example, in the northeast limb of the fold in Figure 3a, a 90 degree change in dip of bedding corresponds to a 72 degree change



FIGURE 3: Cleavage models illustrating angular relations between bedding and:  
a) regional cleavage dipping  $50^{\circ}$  S.W.,  
b) an upward opening cleavage fan,  
c) a downward opening cleavage fan.





in the dip of cleavage; this amounts to an angular decrease in the acute angle of  $8^{\circ}$  per increment of  $10^{\circ}$  in bedding, and therefore amounts to a  $2^{\circ}$  decrease in dip of cleavage for every 10 degree increase in dip of bedding. Figure 3c illustrates the behavior in a downward opening fan with variation as above. The curve shown (++) in 3b, together with (...) shows an irregular fan.

#### Genetic Classification:

Slaty (Flow) Cleavage: Cleavage surfaces are defined by the parallel arrangement of planar minerals. Two principal hypotheses of origin are: the recrystallization hypothesis and the movement hypothesis. These have been reviewed in detail by many recent writers: Badgley (1965), A.G. Jones (1959), Maxwell (1962), and discussed by: Bonorino (1960), Knill (1960), and Talbot (1965).

a) Recrystallization Hypothesis: Flow cleavage is held to be the result of static recrystallization of minerals in folded rocks under stress, such that platy minerals crystallize parallel to planes which lie perpendicular to the maximum stress direction. Many proponents believe that the axis of maximum shortening is perpendicular to the plane of flow cleavage. However, the orientation of the cleavage is accomplished mainly by recrystallization, neocrystallization and gliding rather than by actual granular rotation and shifting. Later stages of folding and/or rotation may cause fanning with attendant slip or bending of the cleavage planes. Alternatively, the development of cleavage might lag behind folding so that cleavage departs from parallelism with the axial planes of fold because the cleavage planes were



'frozen' in a metastable position. Only locally, such as on the limbs of isoclinal folds, can bedding and cleavage be exactly parallel by this scheme..

b) Movement Hypothesis: Flow cleavage results directly from movements within the deforming rock body in response to stresses. There are two main alternatives: (i) cleavage follows one or both of the planes of maximum shear; (ii) it forms perpendicular to the direction of maximum finite shortening by granular reorientation.

(i) Becker (1907) proposed an ingenious mechanism based on the strain ellipsoid by which only one plane of shear was utilised. Some later writers have refuted the theory on the grounds that there is no mechanism in plastic deformation which could completely suppress slip on one of the two conjugate shear planes. The argument is that once shear occurs parallel to one of the potential shear surfaces in a plastic (continuous) deformation situation, strain-hardening would facilitate development of the second, so that signs of both should be present\* (e.g., Bonorino, 1960, p. 305). The more popular two-shear plane version sees two bisecting shear planes activated by a compressive stress so that they begin rotating; rotation continues until the shear planes have 'flattened' so that no further slip is possible. At this point, new shear planes come into play in the original positions and the whole process repeats.

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\* Becker's argument is attractive in terms of discontinuous (ruptural) deformation such as faulting, however.



(ii) Ramsay (1967, p. 180) believes that slaty cleavage in low-grade metamorphic rocks is the result of mechanical reorientation of crystal particles, possibly accompanied by some new growth of micaceous minerals. Like many other workers he believes it is transitional with schistosity in higher grade rocks. The S-surfaces themselves form perpendicular to the direction of maximum finite shortening; at least 30 percent compressive strain usually accompanies slaty cleavage. Because there can only be one direction of maximum finite compressive strain there should be only one true slaty cleavage, even in multiply deformed rocks. The principle goes back to Sorby's 1853 experiment in which flakes of hematite in stiff pipe-clay were subjected to compression and became aligned normal to the stress.

Fracture Cleavage: S-surfaces are defined by closely spaced parallel fracturing which is independent of any parallel arrangement of the mineral constituents of the rocks which are cut. Three major hypotheses of origin for fracture cleavage as a distinct phenomenon are most commonly encountered.

a) Interbed-shear origin: cleavage may develop almost perpendicular to bedding initially; it is related in origin to external stress acting on bedding to set up two potential shear surfaces: one parallel to bedding and the other parallel to the potential cleavage surface.



The  $2\theta$  angle is initially 90 degrees, but interbed slippage increases as the angle between initial cleavage and bedding goes beyond 90 degrees in the course of folding. Each rotated slice must be relatively thin since otherwise the cleaved bed would thicken rather than be thinned as is the usual case. Badgley has gone on record as favoring this origin for first generation fracture cleavage in 'competently folded rocks' (Badgley, 1965, p. 294), but cleavage could develop by interbed shear in either or both competent and incompetent beds. The amount of actual 'bending' or rotation of S-surfaces would be greater in less competent units, for example thin argillites in an interbedded sequence.

b) Tensional Origin: Knill (1960, p. 320) feels that the interbed shear hypothesis cannot adequately explain the development of fracture cleavage in the crestal areas of folds. He feels that fracture cleavage develops as tensional cracks early in folding, and that is initially normal to bedding. With increasing deformation the S-surfaces are either fanned as the result of folding, or alternatively they remain axial plane structures if differential slip takes place along both the fracture cleavage and the folded surface. Either condition could result from brittle rupture during folding. The hypothesis is adequate for axial-plane fracture cleavage and for upward fanned cleavage, but it is difficult to visualize this mechanism in cases where such fracture



cleavage fans downward in anticlines and upwards in adjacent synclines. De Sitter (1956, p. 99, 100) reports that it has been his experience to find both slaty and fracture cleavages approximately parallel to fold axial surfaces, the latter foliation often being penetrative in shales but cutting sandstones and limestones only in anticlinal or synclinal regions, or fanning downward, whereas slaty cleavage planes more often converge downward.

c) Shear Folding or Microlithon Origin: Fracture cleavage is interpreted as a non-tensional phenomenon resulting from a vertical shear couple which causes differential movement along planes perpendicular to the largest principal stress. This produces a flattening of the rock in a direction parallel to the maximum principal stress direction (de Sitter, 1956, p. 97), as the result of slip by plastic stretching of microlithons in accompaniment to shear folding. Two variations are commonly illustrated in literature: a symmetrical type, in which there is an alternating sense of slip in adjacent microlithons; and an asymmetrical type, which differs from the former in that material on opposite sides of a laminar microlithon moves in opposite directions so that the sense of shear on a given side of an S-surface separating microlithons is always in the same direction.

A similar idea is the 'compression schistosity' mechanism proposed by Turner and Verhoogen (1960, p. 653) whereby mechanically weak materials flow into a plane of low



shearing stress normal to the maximum compression axis.

Badgley believes the microlithon origin is common in incompetent rocks which are undergoing plastic deformation.

Slip (Strain-slip) Cleavage: It is generally agreed that slip cleavage is the result of shearing because almost invariably there is evidence of movement along S-surfaces, and because there is a relative absence of recrystallization. Turner and Weiss (1963, p. 46) indicate that the surfaces of slip are not discrete fractures, but simply somewhat laminar domains of intense strain which may become the foci for syntectonic or post-tectonic recrystallization of mica, ultimately leading to the development of schistosity. The 'movement school' does not distinguish between flow- and slip-cleavage, except in degree of recrystallization.

The terms 'slip' or crenulation' cleavage have been applied to structures ranging in size from plicated mica flakes through types of 'Gleitbretter' structure and bent or folded slaty cleavage or schistosity. In view of the uncertainties as to whether or not such S-surfaces are late first generation, second generation, transitional, or perhaps any of these singly or in combination, crenulation cleavages should always be described as such initially. Their precise nature should be determined and described in greater detail than is the usual practice.



Bedding-Plane Cleavage: Extreme flattening and shearing, as in areas characterized by tight isoclinal folds or nappes, may produce a foliation essentially parallel to the original bedding or compositional banding. It can occur on both local and regional scales.

Composite Origin of Rock Cleavage: Many observers have suggested that slaty and fracture cleavage have a common origin.

a) 'Buckle fold Dilatation' Origin -- Ramsay (1967, p. 406) cites the passage of 'fracture' cleavage in graded beds into slaty cleavage without any appreciable break (though it may be 'refracted' at sharp lithological boundaries) and suggests that the special features of fracture cleavage are merely the result of modifications undergone by slaty cleavage during later stages of folding. He feels that during the folding of an interbedded sequence the buckled competent layers can push against and displace less competent jacketing material to some extent. But beyond a certain point further strain increments would require the hinges of adjacent (overlying) folds to separate more than is possible by simple buckling. Further separation could be accomplished by shearing along previously formed slaty cleavage, movement along such zones of weakness being accomplished by physical displacement of the contacts between lithological layers into a series of steps. If the slaty-cleavage planes show a refracted pattern near



the contact between competent and incompetent units then the slip will open up cracks and fissures wherever inhomogeneities cause convergent slaty-cleavage fans. These cracks constitute fracture cleavage and the strain state of the material between actual shear planes generally remains unmodified and is still related to the main slaty-cleavage formation (Ramsay, 1967, Figure 7-74, p. 408).

In thick competent units overlying each other (Ramsay, Figure 7-81 B) there will be open space in the hinge zones of folds unless incompetent material is available to take up the space by flowing into it; if not, box folds or limb-thrusts may form.

b) 'Shear-Normal-Flow' Hypothesis of Origin -- Bonorino (1960) has proposed that all cleavages have a common genetic origin. He believes that in a mixture of spherical quartz and elongated mica under compression there is a relative shearing displacement between spherical grains which is dependent on the inclination of their common tangential plane. Displacement between grains proceeds as 'flow' perpendicular to compression, elongated particles being rotated toward a position parallel to the 'flow' direction with any recrystallization being aligned in the same direction. The mechanism combines the action of the two slip planes equivalent to the planes of maximum shear stress situated about



45 degrees from the maximum stress. The foliation is a 'compromise' plane, its position marking the net result of rotation of mineral particles by the two opposing shear components. The magnitude of rotational components, a direct function of the angle between a mineral grain and the slip plane, diminishes until a point is reached where two opposing movements cancel each other and rotation stops. If the tectonic forces are directly opposed the foliation will bisect the angle between the slip planes; if it is eccentric (rotational) the foliation will have been rotated in the direction of the more active component. Ideally, both slaty and 'fracture' cleavage should therefore be axial-plane structures, but inclined cleavages could also result. No visible S-surfaces could develop parallel to the shearing planes by this mechanism, except those marked by fractures in pebbles, deformation lamellae in quartz, and so on.

In summary, composite origin cleavage theories attempt to explain all foliations in terms of one or more related mechanisms, each gaining the upper hand at some stage of folding. However, the precise relationship between foliation and folding, both in terms of time and space, continues to be a baffling problem. Pre-folding and post-folding foliations can at least be positioned in time but the more prevalent case, that in which foliation has developed under the same set of stresses that folded the beds, is much harder to work with.



Bonorino (1960) has suggested that straight, parallel S-surfaces are most commonly late- to post-folding, the S-surfaces appearing by mechanical orientation and recrystallization; most axial-plane foliations reach the climax in their development when folding is essentially complete, he says. In folded interbeds of shaly and quartzitic composition the difference in plastic response to deformation (? ductility contrast) produces local modifications of the general stress field leading to departures of the S-surfaces from the axial-plane position. Such modifications include: 1) 'refraction' of foliation, which he interprets by two dimensional resolution of stress vectors; and 2) a predominant inclined foliation due to interstratal slip which imposes a slight eccentricity to the local stress in incompetent beds along the flanks of folds.

Later movements, which may cause micro-folding of an earlier S-surface, could produce slip along S-surfaces without mineral reorientation (Bonorino's 'fracture' and 'slip' cleavages).

General Discussion: There is a tendency for some of the above classes to overlap. Attempts to justify certain peculiarities of one class in terms of physical parameters, of which we know comparatively little, often produce new problems such as trying to explain why exceptions to the new rule are equally evident in the



data. Other approaches make use of elaborate mechanical theories, sometimes based on strict mathematical models, but of the geological applications of these we know even less.

This state of affairs has led some workers to condemn all classifications categorically. Such grand cutting of the 'Gordian Knot' in itself offers no progress toward solution of the problem. Eclectic or not, any broad classification of complex phenomena which is reasonably free from bias even if not completely exclusive in nature offers the investigator a point of departure, a system by means of which he can roughly position himself in the three -- it should be four -- dimensional continuum in which he must do his thinking. Axioms in geology are hard to come by; surely they should not be postulated merely to sidestep the confusion resulting from apparently contradictory observations.

Generalizations regarding the origin of cleavage are few. Fracture cleavage and crenulation (strain-slip) cleavage almost invariably show signs of actual or incipient shear; clearly movement of some sort is instrumental at least in the last stage of their development if it is not in fact related to their origin. Both types are less penetrative on most scales of investigation than are slaty cleavage or bedding-plane cleavage (schistosity). All of them are controlled to some extent by localized inhomogeneities existing in the rock at the time of foliation development.



Both slaty cleavage and bedding-plane schistosity are best developed in units which are compositionally or texturally homogeneous. Slaty cleavage develops best and is least variable in fine-grained, dominantly argillaceous rocks; its relative degree of penetrativeness reflects variations in composition or in degree of deformation. The commonly reiterated observations: 1) that slaty cleavage is refracted around competent inclusions (Charlesworth and Evans, 1962) and 2) that slaty cleavage planes converge toward the region of highest strain (Ramsay, 1967; Hills, 1963), suggest that slaty cleavage forms in a stress field. But: 3) the frequently corroborated observations of Sharpe and Sorby regarding the elongation of deformed objects in a direction parallel to cleavage, and 4) the work of Cloos (1947), which suggests that slaty cleavage can indicate compressive strain in excess of 30 per cent, would seem to corroborate the view that slaty cleavage follows the plane of maximum finite strain.

Nevertheless, a century of debate has failed to resolve the mechanism responsible for the preferred orientation of micaceous minerals in slates. Logical extension of either the movement hypothesis or the crystallization hypothesis should also explain fissility in undeformed clays upon compaction, but as Whitten (1966, pp. 227, 228) has pointed out, there is little evidence to support or deny the upper hand to either mechanism over the other in that process.



Some investigators feel that both mechanisms can operate, probably in different environments but possibly in different parts of the same domain.

Most of the observable characteristics of slaty cleavage can probably be accounted for in terms of local stress configurations in a developing fold. Deformed objects lying in the plane of cleavage must surely indicate a relative shortening of the deformed body in a direction perpendicular to the cleavage. Elongation of such objects parallel to slickensides, a feature observed by Sorby and Sharpe over 100 years ago (Cloos, 1946, pp. 51 52) seems to point to predominance of shear (extension) over laminar (rheid) flow parallel to cleavage (cf Turner and Weiss, 1963, pp. 456-460).

The roles of neomineralization must however remain a mystery since indirect componental movements could occur at any time. On the other hand 'pressure shadows' and rotated porphyroblasts suggest that at least some crystallization is syntectonic.

Relation to Associated Structures.

Foliations, lineations and folds share certain simple geometrical relationships:

- 1) Foliation is commonly parallel to or symmetrical about the axial surfaces of folds in an earlier S-surface, usually bedding.



- 2) Lineation usually parallels or lies normal to the axes of folds, depending on its type.

Overprinting or interference in space, or in both time and space, by several classes of structures may, however, obscure these simple relationships. At present, the techniques for analysis of superposed structures have not been refined enough for more than simple interpretations of geometric relations.

### Macroscopic Fabric

Macroscopic domains include bodies of a scale too large or too poorly exposed to be subject to direct examination in their entirety. Analysis of such domains involves much extrapolation from mesoscopic data. Since a homogeneous macroscopic fabric is defined by mesoscopic structures which are penetrative on the macroscopic scale there can be but few fabric elements because only a few structures can satisfy the requirement of being too large for classification as mesoscopic yet small enough to be penetrative on the macroscopic scale.

Macroscopic structures include folds, faults, unconformities and other non-penetrative structures; macroscopic folds are the most commonly studied of these since they can be present without destroying the homogeneity of mesoscopic domains. The most commonly studied fabric elements in macroscopic analysis are mesoscopic S-surfaces, lineations, axes and axial planes of folds, and perhaps arrays of microscopic structures or domains. Neither



sampling nor analysis can be 'statistical' in more than a purely qualitative way.

Analytical procedure must be designed for the problem at hand. It is usual to focus on the most prominent S-surface in the domain, usually bedding in sedimentary terrains. Since measured segments of folded beds are always planar, the pattern of preferred orientation of other prominent S-surfaces in a number of domains which are homogeneous with respect to the same structure can provide valuable clues regarding the form and nature of the macroscopic folds. Foliations, for example, serve as a rough gauge of the degree of penetrativeness of the macroscopic deformation.

Analysis of an area such as that near Jasper, an area in which folding of various types and on various scales has taken place in fairly regular fashion, may be approached on the assumption that large and small folds and their associated features have generally conformed to "Pumpelly's Rule." The relationship appears to be true for many areas, not only areas in which cylindrical folding predominates, but wherever there are superposed structures of all sizes. Turner and Weiss (1963) suggest that: "In any tectonite body, however complex its structure, it is generally possible to find a hand specimen or a single exposure in which all the geometric properties of the macroscopic body are displayed on the mesoscopic scale."

The balance of this thesis may be regarded as an attempt to test that hypothesis.



## A FABRIC STUDY IN THE JASPER AREA

### Introduction

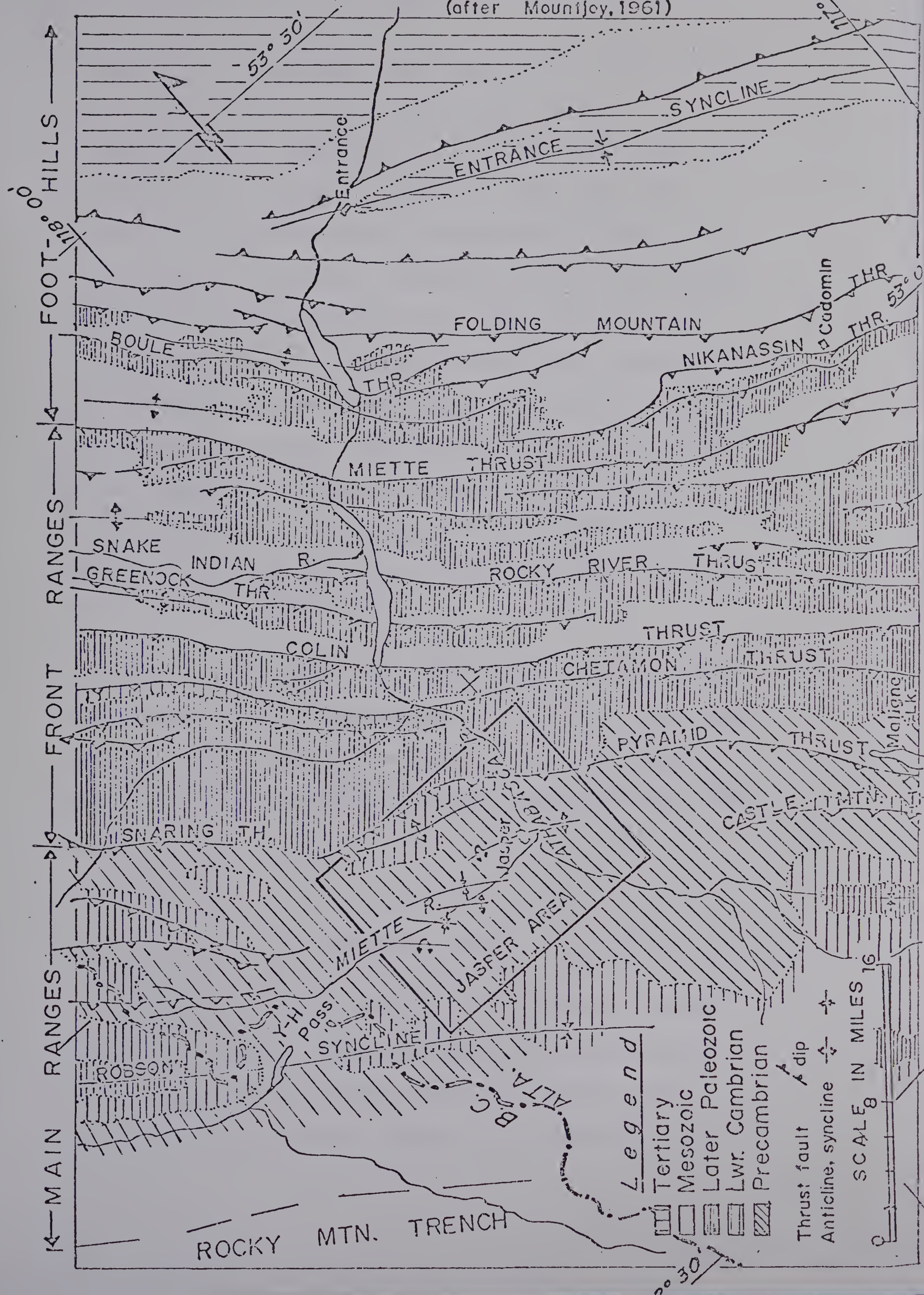
The district here referred to as the Jasper area lies in the hanging wall of the Pyramid thrust fault in the Main Ranges of the Rocky Mountains (Figure 4). At this latitude the Pyramid thrust separates Proterozoic and lower Paleozoic rocks of the Main Ranges on the west from the Paleozoic and Mesozoic rocks of the Eastern of Front Ranges, which lie to the east-northeast of the town of Jasper.

Previous investigators have divided the ten thousand feet of Proterozoic and Lower Cambrian strata exposed near Jasper town into two groups: 1) the Gog Group, comprising about 5000 feet of cliff-forming sandstones and quartzites, and 2) the underlying, more recessive, Miette Group of interbedded coarse-and-fine-grained clastics, also about 5000 feet thick. Early Cambrian fossils have been found in the upper part of the Gog Group (Mountjoy, 1962), but no visible unconformity has been found between any of the older rocks in the Jasper region. This has led to provisional drawing of the Precambrian-Cambrian boundary at the base of the Gog Group (Charlesworth et al, 1967).

The Precambrian-Lower Cambrian succession has been divided into five apparently conformable formations



FIGURE 4 Regional setting of Jasper area (see Fig. 5).  
(after Mounsey, 1961)





(Figure 5). In ascending order the rocks of the shallow-water, marine and deltaic Miette Group consist of:

- 1) Conglomerates, sandstones, siltstones and slates of the Meadow Creek Formation (Weiner, 1966) only the uppermost 130 feet of which are exposed, 2) about 1200 feet of slate, siltstone, limestone-breccias and bedded limestones known as the Old Fort Point Formation, and 3) conformably overlying the Old Fort Point, some 4000 feet of conglomerates, sandstones, siltstones and slates of the Wynd Formation. Conformably overlying the latter is the lower part of the Gog Group, consisting of:
- 4) 1500-2000 feet of conglomerates and feldspathic sandstones, called the Jasper Formation, and 5) 900 feet of quartzite designated Unit A.

All of these rocks have been folded and are cut by thrust, normal and wrench faults. The Miette Group has suffered slight regional metamorphism and no evidence of significant igneous activity in the region has yet been found.

#### Methods of Study

Previously mapped outcrops in the better exposed parts of the Jasper, Muhigan Creek and Meadow Creek anticlinoria and the Minaga Creek and Rathlin Lake synclinoria were visited (Figure 5). Hundreds of outcrop

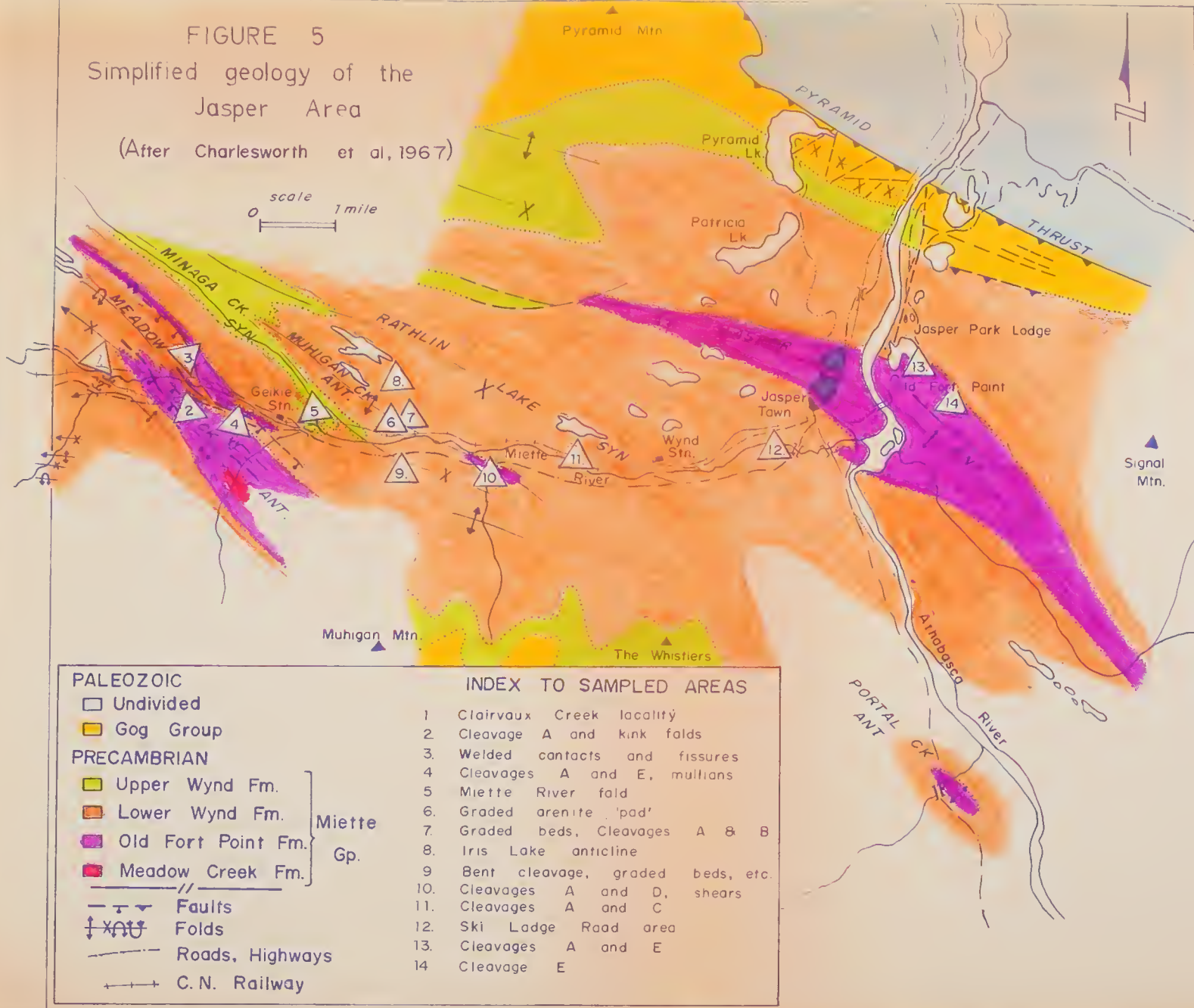


FIGURE 5

# Simplified geology of the Jasper Area

(After Charlesworth et al, 1967)

scale  
0 1 mile





measurements were made, over 120 field photos of mesoscopic relations were taken, and 180 oriented hand-specimens were collected, more than half the latter eventually being reduced to thin-sections for microscopic study and measurement with the universal-stage. In addition to this data, the writer also had access to the several hundred thin-sections and dozens of excellent hand-specimens collected and catalogued by previous workers.

### Mesoscopic and Macroscopic Geometry

Three regions with contrasting tectonic styles comprise the central Alberta Rockies, namely: 1) the Foothills on the east, adjoining the Plains; 2) the Eastern or Front Ranges, and 3) the Main Ranges. Within these divisions, from eight to ten parallel thrusts have disrupted the stratigraphic sequence. The thrusts themselves are splays off three principal zones of decollement: a) a Proterozoic zone under the Main Ranges; b) a Cambrian zone under the Eastern Ranges; and c) an Upper Paleozoic zone under the Foothills. Mountjoy (1962) has suggested that thrusting was probably initiated in the southwest with successively younger thrusts originating beneath and to the northwest of the older ones. Bedding surfaces and most of the fault surfaces themselves have been folded. No basement rocks have been recognized anywhere in the Rocky Mountains and seismic evidence suggests that the 1600-1900 m.y. old



Churchill Province of the Canadian Shield which underlies the Plains also continues beneath the mountains (Bally et al, 1966).

The Main Ranges, about 45 miles wide near Jasper, are bounded on the west by the Rocky Mountain Trench and separated from the Front Ranges to the east by the Pyramid and Snaring thrusts, both of which come to the surface a few miles north-northwest of Jasper town. Stratigraphic throw on the Pyramid thrust at Pyramid Mountain appears to be on the order of 10,000 feet so that Devonian and Mississippian rocks of the footwall adjoin the early Cambrian Jasper Formation of the hanging wall. Regional trend of the Main Range structures in the vicinity of Jasper is about N 55°W.

#### Macroscopic Structure

The Precambrian rocks of the Athabasca and Miette River valleys lie in a series of open to tight folds, the enveloping surfaces of which have themselves been folded into three northwest trending anticlinoria and two intervening synclinoria. Limbs of these structures dip at from 25 to 50 degrees.



## Mesosopic and Microscopic Structures

Folds: All mesoscopic folds in the Precambrian rocks of the Jasper area are tight and fairly evenly spaced along the limbs of the principal macroscopic features. Other general characteristics are:

1) Mesoscopic folds in the Old Fort Point strata are spaced about 300 feet apart, with apical angles progressively tightening from 65 degrees in the eastern part of the region to 30 degrees in the west. Almost invariably, minor folds are inequant, their northeast limbs having suffered thinning. Inclination both of the opposing limbs and of the axial surfaces decreases (flattens) westward.

2) Mesoscopic folds in the lower Wynd Formation are more widely spaced (about 500 feet), and their axial surfaces are nearly vertical across the entire outcrop belt. Apical angles average about 60 degrees, but the folds are still inequant in shape.

3) Mesoscopic folds in the lower part of the upper Wynd are tight and very closely spaced.

4) Mesoscopic folds do not appear in the uppermost Wynd, but both the upper Miette Group and Gog strata have been folded on about the same scale as the underlying anticlinoria and synclinoria.

5) Geometrically most minor folds are plane cylindrical



to non-plane cylindrical, depending on the scale of measurement; style, symmetry and size vary but little though there are minor variations in orientation along the flanks of the major features.

6) In terms of symmetry, folds in the Old Fort Point Formation are generally monoclinic, sometimes triclinic (?); Wynd folds are usually orthorhombic.

7) Cleavage is prominent in folded rocks of the Old Fort Point and lower Wynd Formations, especially in rocks of argillaceous nature.

Foliation: Charlesworth et al (1967) differentiated five types of metastructural foliation in the Jasper area. Their alphabetical system of nomenclature will be used here, in conjunction with the usual subscript notation used when referring to 'S-surfaces'. The five major types must be inferred to be the result of one period of deformation since there is no evidence of any major disturbance subsequent to the development of major and minor folds, and little evidence to suggest appreciable deformation prior to such an episode.

#### Cleavage A

This foliation results from the preferred orientation of metamorphic muscovite and chlorite, and is penetrative in most micaceous rocks of the Miette Group. It is



especially prominent in slates of the Old Fort Point Formation but is also important in rocks of the lower Wynd Formation. It is not penetrative in argillaceous rocks of the upper Wynd Formation or in Cambrian strata.

a) Mesoscopic Description--

Generally, very fine-grained slates can be split along microscopic S-planes into thin, smooth, planar sheets usually less than 1 mm thick, but as the content of coarse material increases the parting becomes wider-spaced and the cleavage surfaces become rougher (Figures 24,27).

Geometrically, Cleavage A is primarily an axial plane foliation, though it also fans symmetrically about the axial surfaces of folds. The first attitude is most common in the upright folds of the lower Wynd Formation (Figure 12a). Occasional deviations occur in argillaceous rocks in the axial regions of anticlines (e.g. Iris Lake anticline: Bielenstein, 1964 and present Figure 13a).

Charlesworth and Evans (1962) plotted cleavage dip against the dip of bedding in Old Fort Point slates of the Jasper Anticlinorium using data from slates as devoid as possible of interbedded siltstones and breccias. They found that cleavage dip increases at the rate of 2 degrees for every 10 degree increase in the dip of bedding to the



southwest, but that it decreases at the same rate for beds dipping northeast. When replotted in terms of the acute angle between bedding and cleavage (Figure 6) their results closely correspond to the model in Figure 3b.

Evans (1961) suggested that in thick homogeneous argillaceous units of the Old Fort Point Formation this tendency for cleavage to depart from a mean plane is probably zero, since the orientation of cleavage is affected mainly by the presence of interbedded competent materials. Where beds are relatively thin the extremities of Cleavage A planes often curve toward the bedding normal near contacts with competent units (Figure 25). Cleavage A in relatively thin bedded slates also tends to be rotated toward bedding (Charlesworth and Evans, 1962, p. 358; present Figure 8), probably as the result of bedding-plane slip between different lithologies. Local deviations also arise where S-surfaces converge toward anticlinal or synclinal apices, and where cleavage is deflected around competent inclusions (nodules or breccias; the observation is certainly valid wherever the presence of bedding-plane slickensides attests to slip between the units, but where the interbedded units are thin or have 'welded' contacts (see below) the generalization is not strictly valid.

Weiner (1966, P. 84) reported that he was unable to discover the relationship between bedding and cleavage reported by Charlesworth and Evans. However, a replotting of Weiner's data for the Meadow Creek Anticlinorium (Figure 9)



readily shows up similar relations between bedding and cleavage: 1) there is the suggestion of a regional element in Cleavage A (cf. Figure 3a) reported by Charlesworth et al (1967, p. 42); 2) Cleavage A in the southwest limb fans upwards, decreasing in inclination by  $2^{\circ}$  for every  $10^{\circ}$  change in the dip of bedding; 3) cleavage in the overturned northeast limbs of folds (average dip  $60^{\circ}$  SW) is erratically fanned so that it approximates the axial surfaces but dips both towards bedding and away from it (cf. Figure 3b).

Figure 15 illustrates the behavior of Cleavage A in Old Fort Point slates in the core of the Muhigan Creek Anticlinorium. As in the Jasper Anticlinorium, the fanning is irregular but here Cleavage A and bedding enclose greater angles on the overturned limb. Cleavage A shows less tendency to diverge from an 'axial-plane' orientation as the southwest limb is descended.

#### b) Microscopic Description--

In thin section, the host rock is separated into laminar domains bounded by micaceous zones on the order of 0.2 to 0.07 times as wide, such that from 20 to 50 domains together with their boundary zones can be crowded into a 1 mm wide slice of slate. Cleavage A is here defined as consisting of the boundary zones, usually 0.0025 to 0.0035 mm (about 3 microns) wide, reasonably planar, and crowded with an aggregate of muscovite and



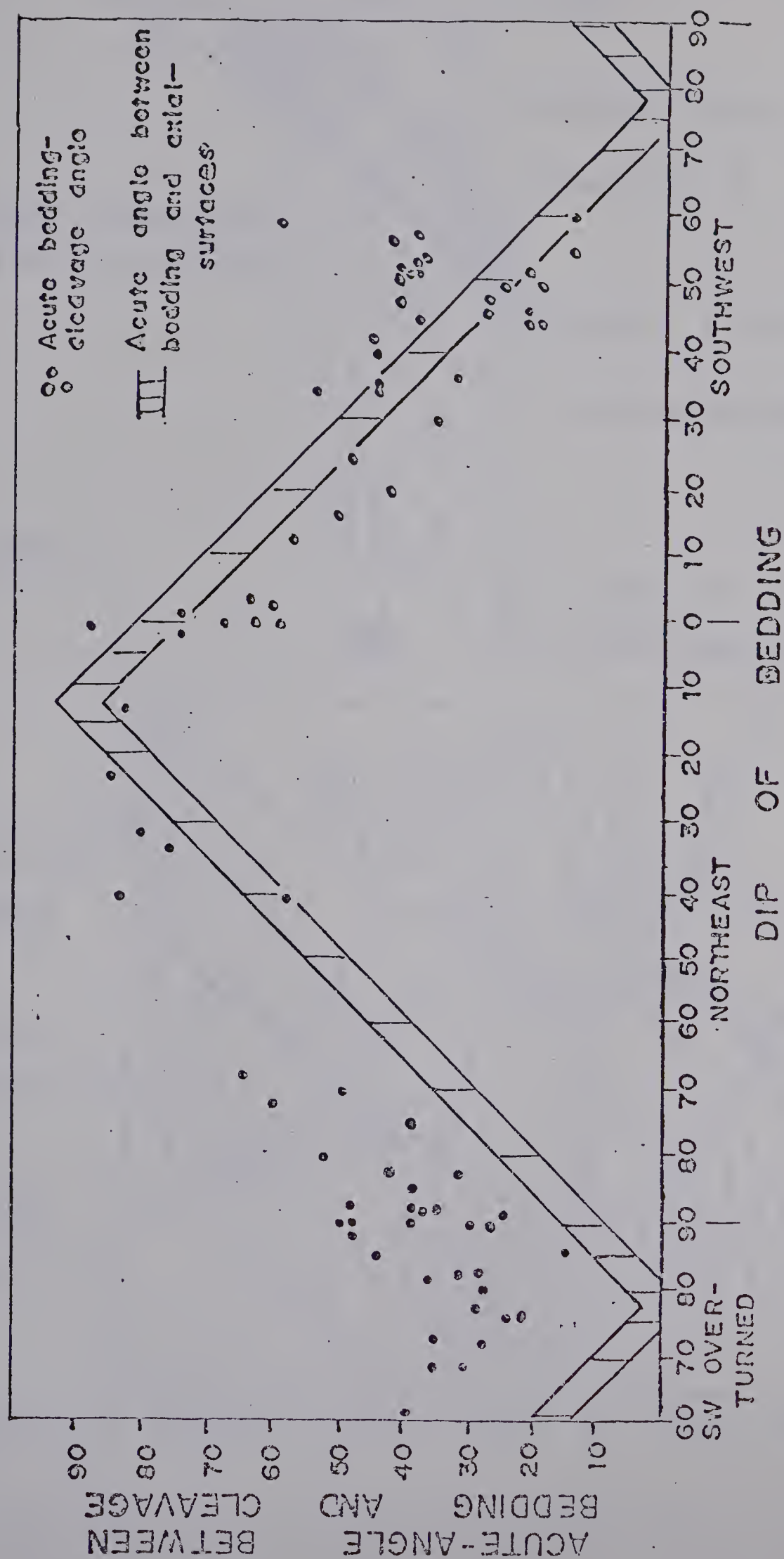


FIGURE 6 Cleavage A in relation to bedding and axial surface in folded Old Fort Point slates of the Jasper Anticlinorium.



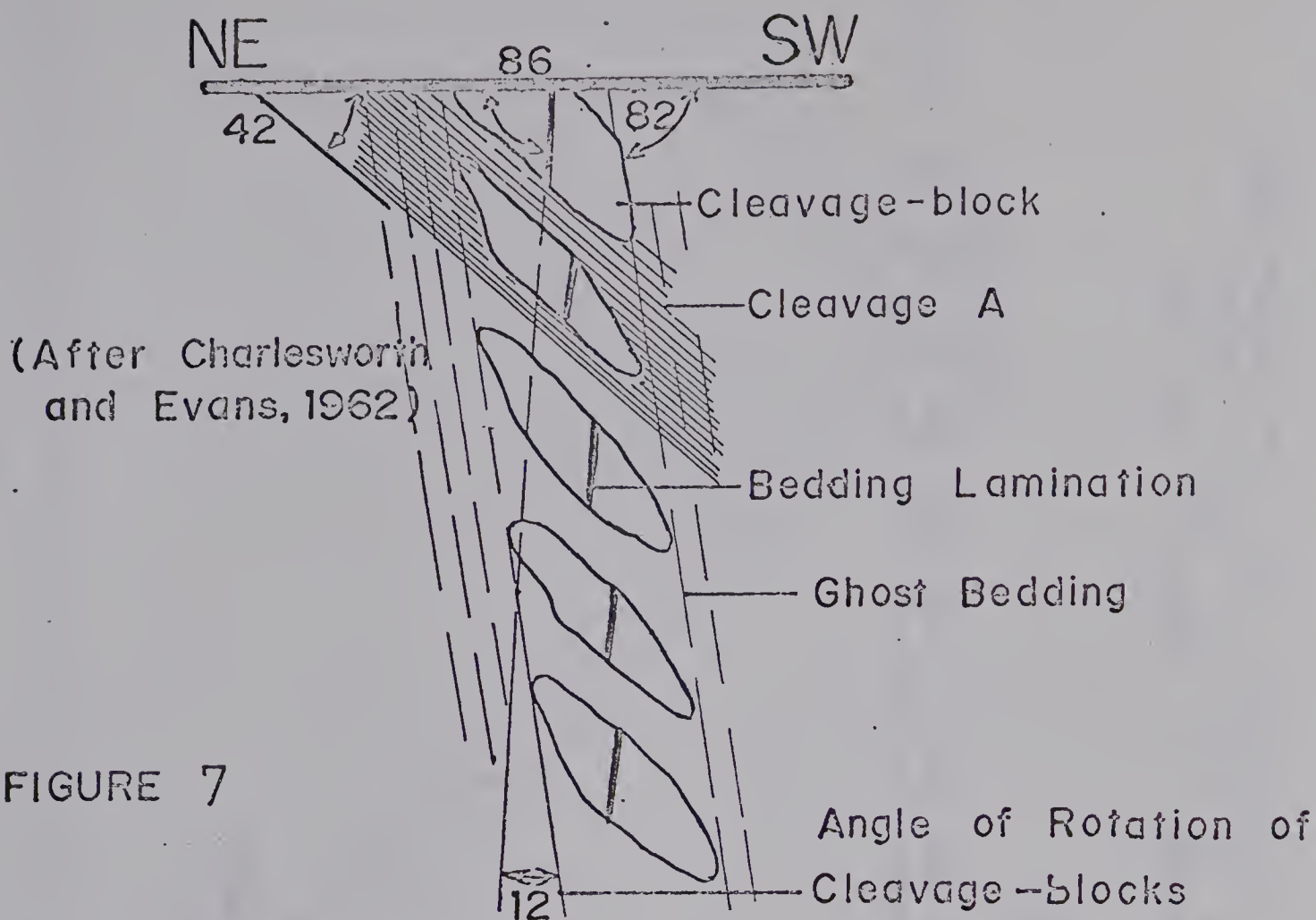


FIGURE 7

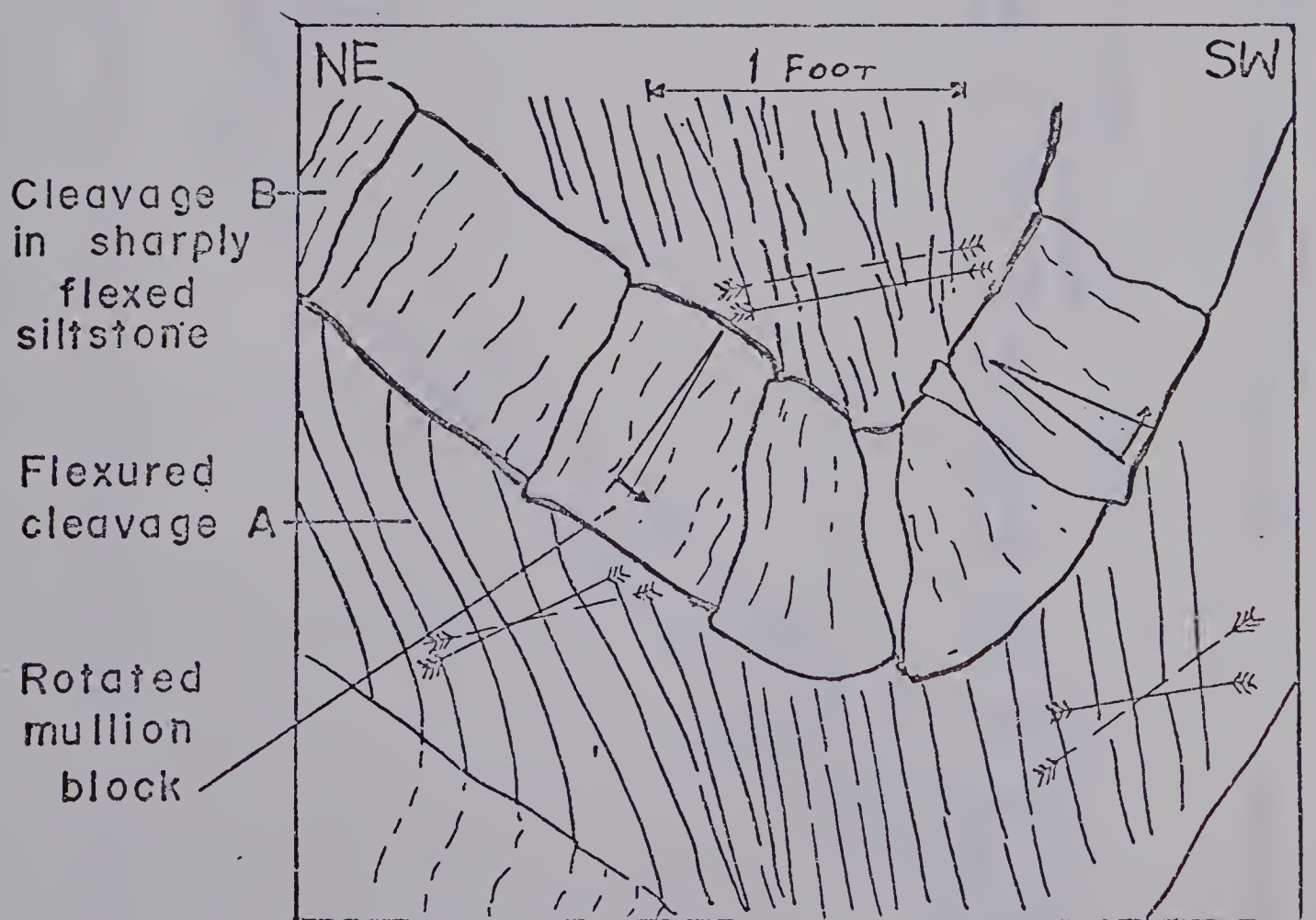


FIGURE 8 (Based on field photo by Evans, 1961).



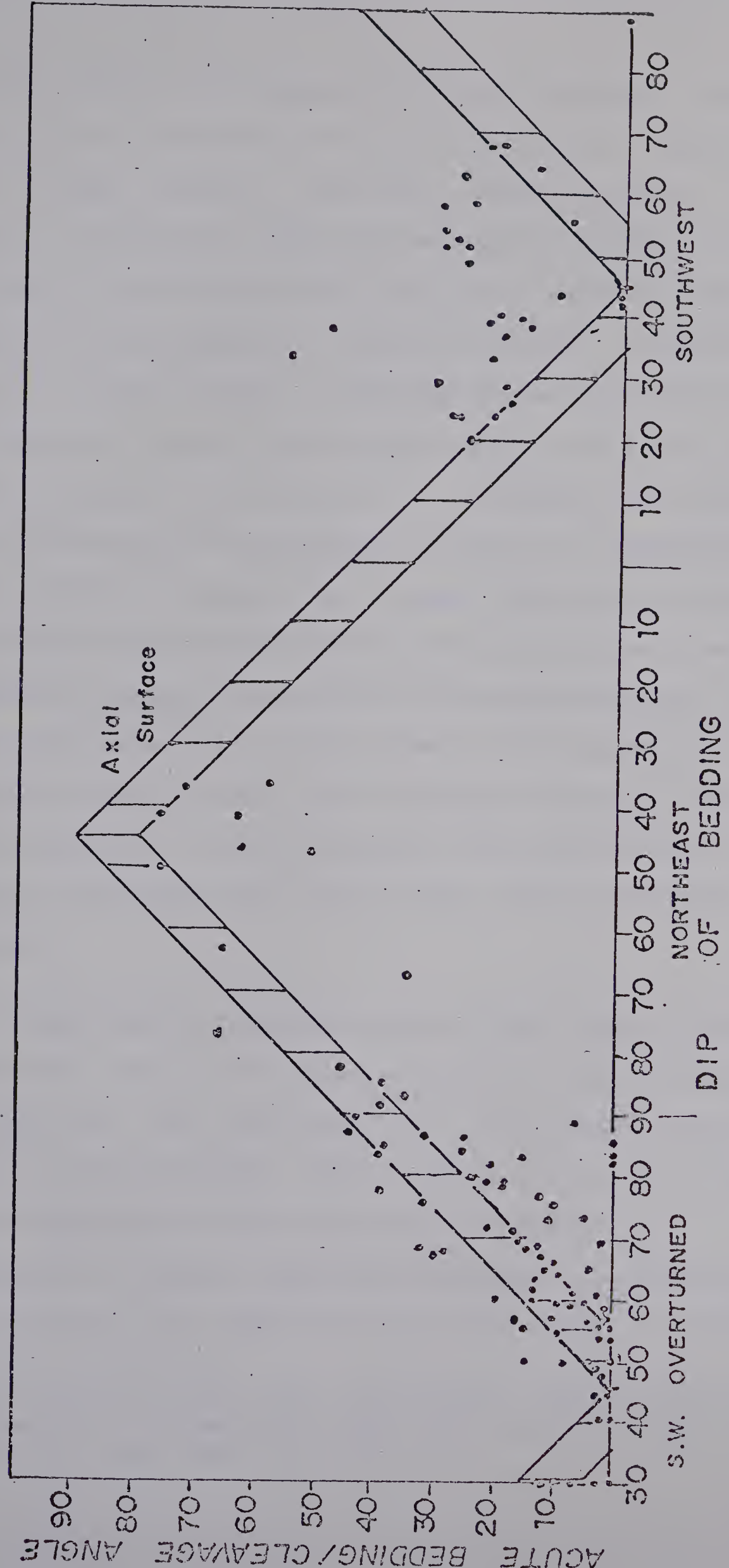


FIGURE 9 Relations between Cleavage A, bedding, and the axial surfaces of folds in Old Fort Point slates of the Meadow Creek Anticlinorium (data from Wolner, 1966)



chlorite flakes and books up to 0.05 mm in length, together with a fine, iron-stained dust of undetermined composition. Such cleavage 'domains', hereafter called  $S_A$  planes, are generally spaced less than 0.05 mm apart, the spacing in any given thin-section being fairly consistent in range though varying somewhat in adjacent domains. The material between cleavage planes is composed primarily of chlorite and muscovite together with minute quartz and albite and minor accessory heavy minerals. In domains where 50% or more of the quartzo-feldspathic material is inequidimensional\*, thin sections cut normal to cleavage indicate a strong dimensional correlation between the trend of the cleavage planes, the longest dimensions of micaceous minerals, and the longest dimensions of the quartz and feldspar particles. Much of the mica in the inter-cleavage domains is bent around particles of other material and tends to have a more 'ragged' appearance than mica in the cleavage (however, see below).

Occasionally, throughout the Old Fort Point Formation, ellipsoidal books of chlorite or muscovite up to 0.05 mm in length may occur with both their long dimensions and their c-crystallographic axes at right angles to cleavage. In poorly cleaved rocks the books are tabular to ellipsoidal in shape, their long dimension lying parallel to bedding ( $S_0$ ) but their 'c' axes lying normal to bedding.

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\* The length-to-width ratio of inequant quartzo-feldspathic material in the particle size range considered here is generally less than 4 or 5 to 1.



Books of the latter type are often bent and occasionally kink-folded.

'Bending' and offsetting of bedding along  $S_A$  is common but transposition of bedding is fairly rare (Weiner, 1966, Plate VIII 2).  $S_A$  planes are deflected around siderite grains where these are present (Weiner, Plate X 6).

Thin section study suggests that Cleavage A in the Jasper area can be separated into two broad categories: spectral and interrupted (Figures 10, 11). The spectral group includes all varieties of Cleavage A in which both the cleavage planes and the intervening domains are straight and essentially parallel; the interrupted group includes bent, kinked, broken or otherwise disrupted cleavage planes and domains. Both groups pertain to examination on the microscopic scale, though the interrupted group can occasionally be identified in outcrop or hand specimen.

The spectral group, illustrated in Figure 10, can be further sub-divided into two branches hereafter referred to as Branch 1 and Branch 2 to avoid the use of new or misleading adjectives. Where Branch 1 develops, Cleavage A as described above and illustrated diagrammatically in Figure 10a, can be seen exhibiting marked variation in the width of both the cleavage planes and the inter-cleavage domains such that at 0.5 to 1.0 mm intervals these features



become noticeably narrower than their counterparts between such zones.  $S_A$  planes in these zones occasionally appear to merge where there has been wholesale disappearance of entire inter-cleavage domains over intervals of 0.5 mm along the trend of the cleavage plane. In other thin sections, or occasionally in other parts of the same thin section, such disappearance of inter-cleavage domains and merging of cleavage planes becomes more pronounced so that a new, less penetrative cleavage can be said to be present; it is the latter which is observed on the mesoscopic scale and illustrated diagrammatically in Figure 10b. At this stage fine splinters and angular fragments of quartzofeldspathic material and much broken and 'frayed' looking micaceous material is the sole representative of the original intercleavage material in the new cleavage planes ( $S_{2A}$ ). Bedding, if marked by laminae of relatively coarser material or color banding, is still traceable in the inter-cleavage domains. Figure 10c is exactly the same in so far as the internal fabric of the planes and inter-cleavage domains is concerned, but with one important difference: any bedding lamination in the zones between the wider cleavage ( $S_{2A}$ ) planes is quite noticeably offset on opposite sides of  $S_{2A}$ . Micaceous minerals lying in  $S_{2A}$  are sometimes bent or frayed as well.

In Branch 2, 'type' Cleavage A as defined earlier again shows narrower zones as in Branch 1, but the spacing

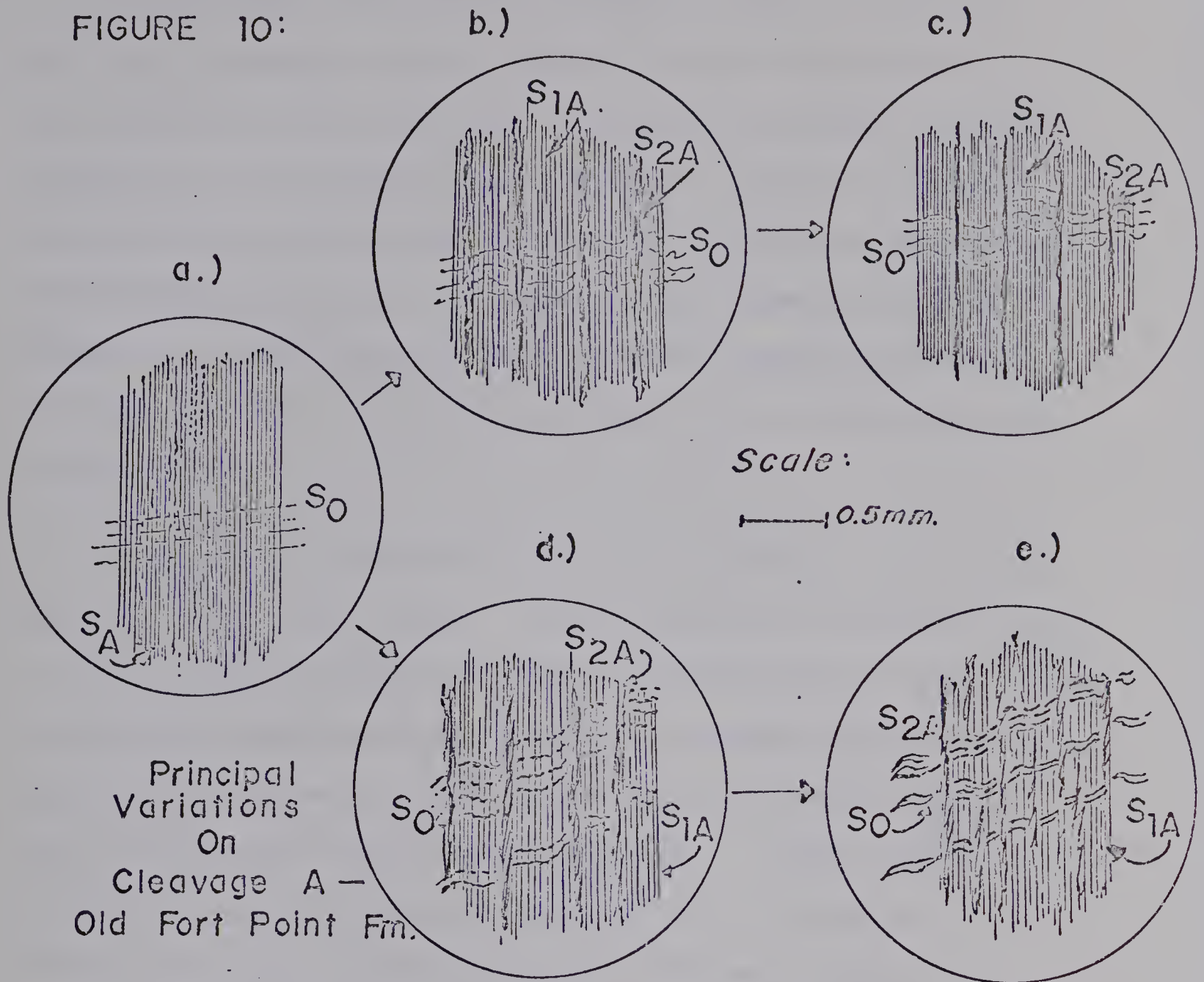


of both 'type' Cleavage A and of the narrow zones is less consistent and almost always at the high end of the ranges given earlier. In domains where  $S_A$  planes begin to merge and the associated inter-cleavage domains start disappearing, (shown diagrammatically in Figure 10d), trace bedding ( $S_0$ ) in zones between the developing  $S_{2A}$  zones shows 'bending' or undulation. Offsetting occurs where  $S_{2A}$  is well enough developed to comprise a penetrative cleavage. Where trace  $S_0$  in the inter- $S_{2A}$  domains shows convergence between adjacent bedding laminae near the outer edges of these domains another (??) set of planes resembling the incipient  $S_{2A}$  of Branch 2 occurs frequently along the steeper parts of the undulations in bedding (Figure 10e).

It is generally possible to find one or more of the conditions just described in a single thin section of Old Fort Point slate, especially in samples collected along the Meadow Creek Anticlinorium. Further work is required in order to ascertain whether the two Branches are indeed different or if they are merely localized responses to deformation controlled by some factor which the writer did not notice. The impression was gained that Branch 1 is most likely to be encountered in homogeneously fine-grained rocks. Branch 2 is most common where sorting was poorer or where numerous coarser-grained laminae are interbedded with slate.



FIGURE 10:



Low-angle Cross-fracturing — Wynd Fm.

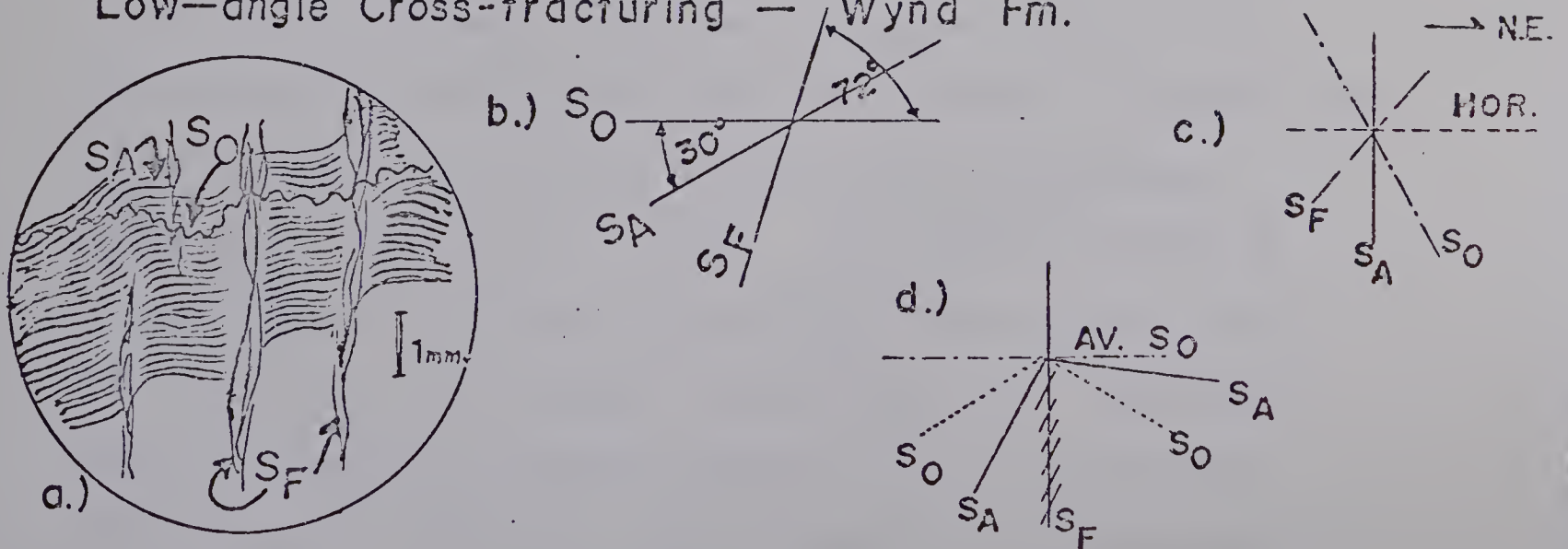


FIGURE 11



Interrupted Cleavage A, as defined earlier, consists of 'type' Cleavage A whose internal and/or external fabric has apparently been modified. Strictly speaking, it should perhaps not be recognized as a distinct category because, thus defined, it includes distinctive classes of structures best treated separately. However, the example shown in Figure 11 cannot properly be described elsewhere without embarking on the interpretative phase of structural analysis prematurely.

Figure 11 illustrates a condition commonly encountered in some lower Wynd slates. Three prominent S-surfaces occur: 1)  $S_0$ , a relict bedding visible as a distinctive color banding or compositional layering; 2)  $S_A$ , a cleavage which contains most of the micaceous minerals in the rock; and 3)  $S_F$ , a set of prominent but irregular 'cracks'. Good examples of this type of  $S_0$ - $S_A$ - $S_F$  triple-play may be found in Griffiths' units 1 and 5 along the northeast limb of the Muhigan Creek anticline, and on both limbs of the Meadow Creek Anticlinorium. As shown in Figure 11  $S_A$  and  $S_0$  both undulate gently across the thin section. The amplitude of  $S_A$  undulations is about 1 mm and their horizontal spacing is about 1.5 to 1.8 mm. On alternate sides of undulation crests there is one steep flank and one which is relatively 'flat-lying'.  $S_0$  in the flat-lying flank appears slightly thickened because of the juxtaposition of  $S_0$  laminae along  $S_A$ .  $S_F$  is present as a population of



discontinuous, straight to curvilinear cracks whose trend can be statistically measured.  $S_F$  cuts both  $S_A$  and  $S_0$  along the steeper flank of the undulations, and minor re-orientation of micaceous minerals in  $S_A$  accentuates  $S_F$ . Figure 11b summarizes the average trend relations as seen in thin section. In Figure 11d the relations in a typical undulation are shown; note that in thin section  $S_A$  is the acute bisectrix of the  $S_0/S_F$  intersection, and that  $S_F$  planes lie oblique to the bisecting plane of the undulations in  $S_A$ . Figure 11c summarizes the mesoscopic relations at the collection site.

Both  $S_A$  and  $S_F$  are best developed in domains where grain size is fine and homogeneous, but whereas  $S_A$  is penetrative throughout the thin section,  $S_F$  varies in its development from place to place and is confined to the steep flanks of  $S_A$  undulations.

#### c) Tentative Working Hypothesis--

The observations recounted above suggest that Cleavage A is subject to local variations in orientation and nature depending on: 1) lithological (textural) homogeneity; 2) the nature of related folds; 3) the nature of internal and external movements during folding; 4) the extent of post-cleavage deformation as indicated by development of new structures or modification of older ones. If valid, the spectral groups indicates that Cleavage A can lead to



'crenulation' type cleavage. In terms of orientation character,  $S_F$  in the interrupted group corresponds to Bonorino's fracture (slip) cleavage (1960, p. 313) and in character it is much the same as Talbot's (1965) crenulation cleavage. In the Jasper area, however, the orientation of the latter ( $S_F$ ) probably corresponds to that of Cleavage B (see below) whereas all spectral group cleavages are near axial plane structures.

Local variations in the development and orientation of Cleavage A are also prominent near arenaceous interbeds and competent inclusions; some of these are also discussed below.

### Cleavage B

Cleavage B is present in poorly sorted arenaceous rocks of the lower Wynd Formation.

#### a) Mesoscopic Description--

$S_B$  is defined by preferentially oriented metamorphic muscovite and chlorite, and by elongated sand size grains lying sub-parallel to the cleavage planes (Charlesworth et al, 1967, p. 44). Spacing of  $S_B$ , generally 2-10 mm, increases with increasing grain size, and may approach the 25 mm range in pebble conglomerates. The nature of the  $S_B$  surfaces is that of irregular planes with a 'hackly' appearance.  $S_B$  surfaces generally are deflected around pebbles or large sand grains. One effect of this behavior



is the separation of the host rock into lensoid domains (Griffiths, Plate VI d) so that a second set of S-surfaces resembling small, wavy joints spaced as much as 0.5 to 2. inches apart may develop.

Charlesworth et al (1967) report that: "Cleavage B fans about the axial surfaces of folds in the normal manner, but it makes a larger angle with bedding than does Cleavage A. Within graded beds, the attitude of cleavage can commonly be seen to change gradually...., in contrast to the abrupt change in orientation at the contacts between rocks of markedly different composition." (op. cit., p.44). Some of the field relations between Cleavage B and fold elements in the eastern part of the Jasper area are shown in Figures 12 and 13. Both figures show that Cleavage B tends to lie at consistently high angles to bedding, generally sub-normal to it, but there is irregular fanning of  $S_B$ . Since the folds described by these two figures refer to structures on opposing flanks of the Rathlin Lake Synclinorium, the two diagrams are not as dissimilar as one might at first suppose; further comments on the behavior of cleavage in the Rathlin Lake structure will follow description of Cleavage C.

#### b) Microscopic Description--

Thin sections of well cleaved arenaceous rocks show  $S_B$  to consist of hackly, irregular, mica-rich domains which separate lenticular, sigmoidal, or diamond shaped zones

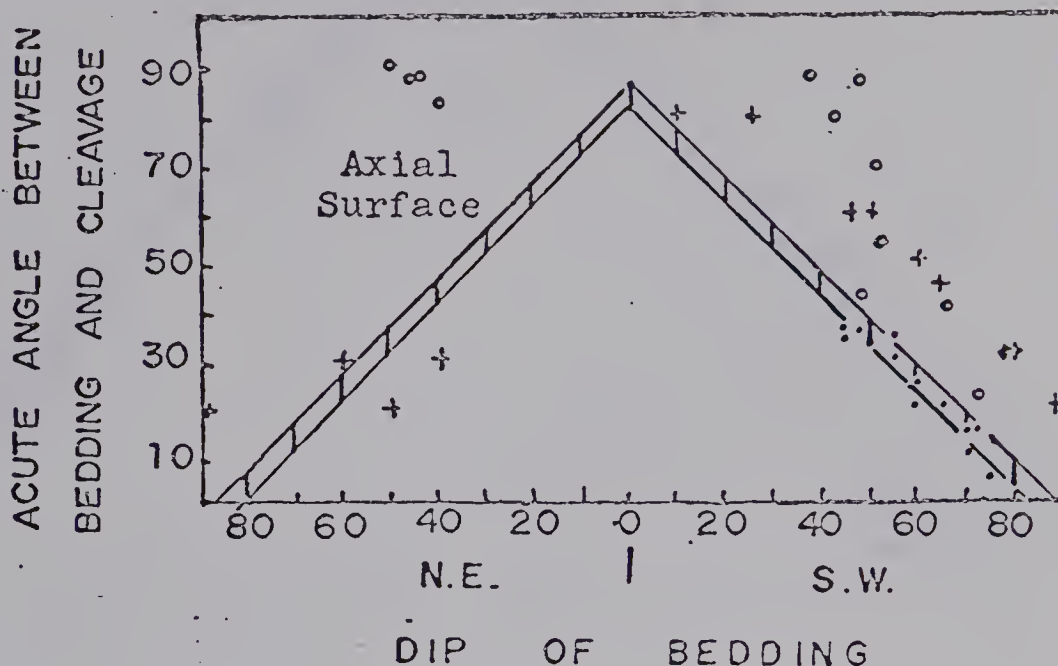


that are penetrative throughout the rock. These zones will hereafter be referred to as sigmoidal domains, regardless of shape, since most of them have that general appearance. These sigmoidal domains have an average width ranging from 2 to 10 mm and a long dimension on the order of 4 to 6 times as great; dimensions of individual sigmoidal domains in a single thin section are quite consistent, and there is good size correlation between thin sections composed of granular material of similar textural grade. Sigmoidal domains are 'stacked' en echelon and there is a tendency for their 'tails' to point in opposite directions. Thus in thin sections cut normal to the bedding/cleavage intersection, the stratigraphically lowermost tail will point toward a synclinal region while the uppermost tail points toward an anticlinal crest. The tendency is best detected in samples collected along the flanks of folds. Each sigmoidal domain is separated from adjacent domains by micaceous domains or zones, generally less than 0.03 mm thick, through which a coarse, sinuous parting may pass. The sigmoidal domains themselves are cut up by finer, irregularly oriented, often discontinuous partings along which micaceous sandwiches or books are aligned. Whereas the coarse partings which outline the sigmoidal domains invariably pass around sand size grains and pebbles, the finer partings within domains always terminate against either grain boundaries or against the coarse partings. Both types of parting commonly show a tendency to converge



FIGURE 12 Cleavage diagrams for the Ski Lodge Road area. Data from Stauffer, 1961.

- a.) All cleavages plotted against bedding attitude (Cleavage  $B=0^\circ$ )  
 (. = Cleavage A, major folds; + = Cleavage A, minor folds)



- b.) Cleavage B replotted to emphasize its dependence on bedding. Note the strong correlation between the dip of cleavage and the dip of the bedding normals.

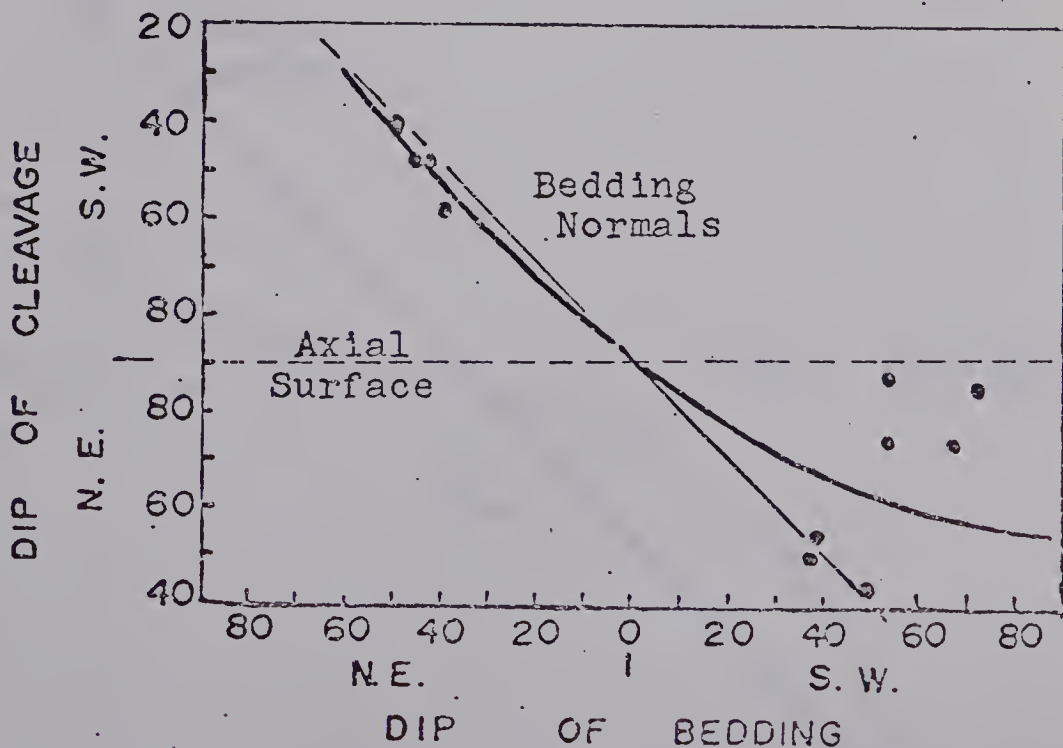
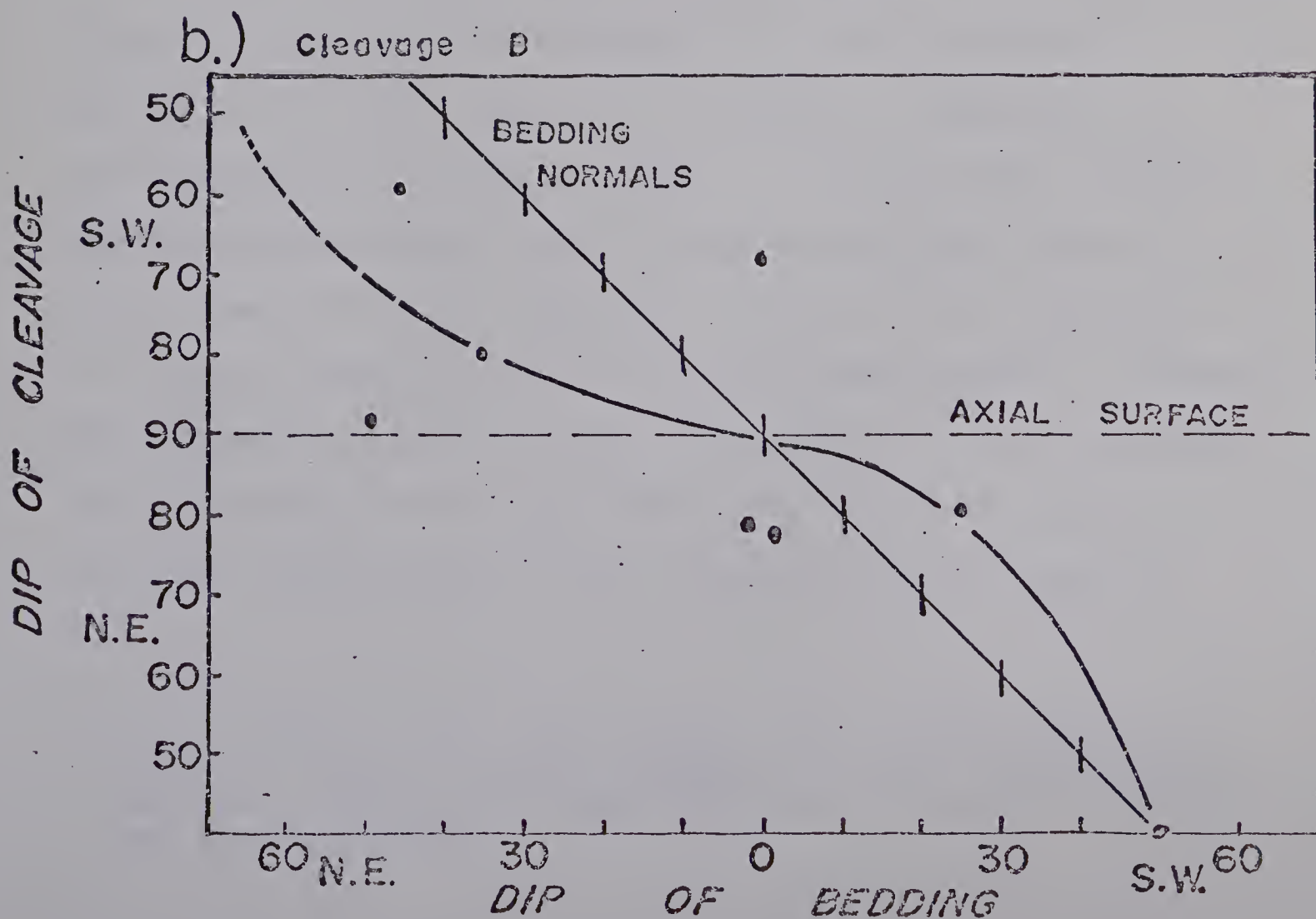
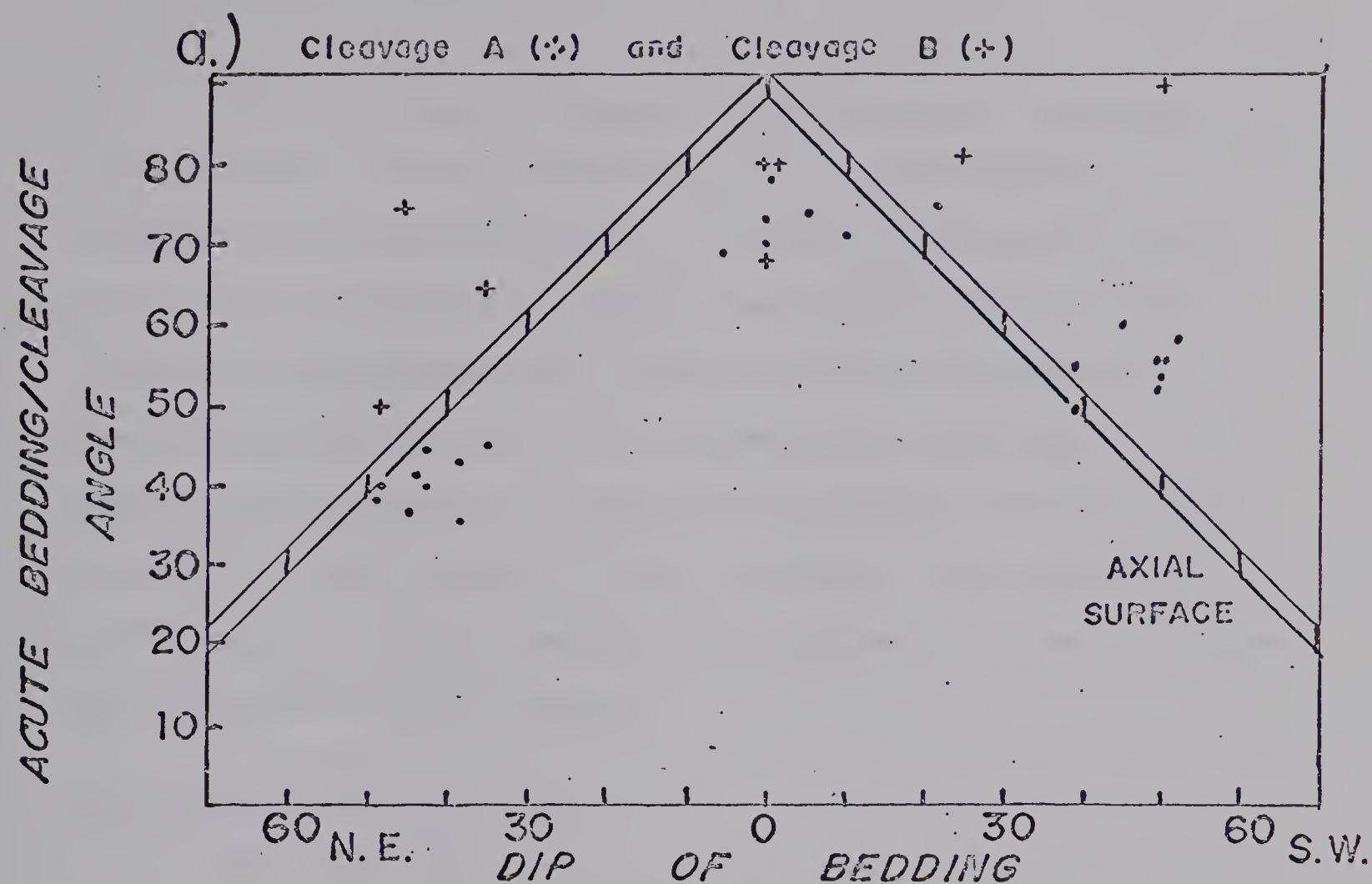




FIGURE 13 Cleavage in the Iris Lake anticline  
(data from Bielonstein, 1964)





upon areas where the number of grain-to-grain contacts per unit area is highest.

Rocks in which Cleavage B is penetrative therefore appear in thin section as though cut by anastomosing sets of curvilinear partings. In most thin sections there is a strong correlation between the trends of the longest dimension of the sigmoidal domains and the long axes of quartzo-feldspathic grains. Because the sigmoidal domains lie en echelon, the micaceous domains which outline them lie at high angles to local bedding. The coarse partings which pass along and through these micaceous domains are the mesoscopic  $S_B$  planes.

c) Tentative Working Hypothesis---

The character of the  $S_B$  planes and of the intervening material suggests that Cleavage B is not a 'fracture' cleavage but rather that it is related to Cleavage A of the argillaceous facies. Since, in buckle folds, tension gashes would normally have an orientation the reverse of that observed for the sigmoidal domains, it is reasonable to suppose that  $S_B$  is not a tensional phenomenon\*. However, the sigmoidal domains do bear a resemblance to the crestward rucking usually associated with both crenulation-type cleavage and parasitic folds developed on the flanks of

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\* In the Miette River fold (Figure 31) tension gashes and a set of tension fractures parallel to the tension gashes both cut Cleavage B, suggesting that the three structures are not co-genetic.



of mesoscopic folds in which the fold core has moved upward (e.g., Badgley, Figure 8-18, after Wilson). Since the individual  $S_B$  planes by-pass competent grains it is not generally possible to establish whether there has been a relative shifting of grains in the sigmoidal domains. The lack of trace bedding away from bedding contacts introduces further complications, so far as kinematic analysis is concerned. However, the writer was able to study contact relations throughout much of the Jasper area and these observations, to be discussed in a following section, may cast some light on the origin of the sigmoidal domains and the orientation of Cleavage B.

#### Cleavage C:

As defined by Charlesworth et al (1967), Cleavage C is similar to Cleavage B in appearance. It also occurs in lower Wynd arenaceous rocks, but apparently is confined to the axial regions of folds.

#### a) Mesoscopic Description--

$S_C$  planes generally parallel the axial surfaces of folds and are associated with actual displacements normal to the fold hinge such that the axial regions of anticlines have moved upwards while those of synclines have moved downwards. Griffiths (1962) first described such axial plane cleavage from the Rathlin Lake Synclinorium (Figure 14). If Figure 14 is inverted, a direct comparison can be made with



Figures 12a and 13a. The axial plane element of Figure 14 is the Cleavage C of Charlesworth et al. The data was abstracted from Griffiths' cleavage map; corrections were made for the difference in strikes of bedding and cleavage, but no correction was made for plunge of the bedding/cleavage intersection which ranges from 0 to over  $45^{\circ}$  west-northwest. Plunge is greatest along the southwest flank of the syncline, and this probably accounts for most of the discrepancy shown in Figure 14. At any rate, the amount of fanning indicated is less than that for Cleavage A in the Jasper region; Griffiths' cross-section in fact shows approximately the same amount of fanning: about  $1^{\circ}$  decrease in dip of cleavage for every  $10^{\circ}$  decrease in the dip of bedding.

b) Microscopic Description--

Thin section examination of rocks from the 'type' area, a locality where micaceous minerals are not abundant, shows that the aspect of the Cleavage C planes is not unlike that of the coarse partings described above as passing through mica-rich Cleavage B domains. But, the sigmoidal domains are neither abundant nor well developed.  $S_C$  partings, therefore, appear to have better continuity and are essentially parallel, except where they deviate around large grains of quartzose material. A finer set of partings with irregular orientations is invariably present in the inter- $S_C$  domains. Broken quartz grains with undulose extinction and a strong preferred alignment of both optical and dimensional elements are abundant in the inter-cleavage domains as well. Where bedding lamination is present, offsetting is in the same



FIGURE 14 Cleavage in the Rathlin Lake Synclinorium. Data abstracted from cleavage map by Griffiths, 1962. Note the similarity between this axial plane structure and Cleavage A in Figures 6 and 9.

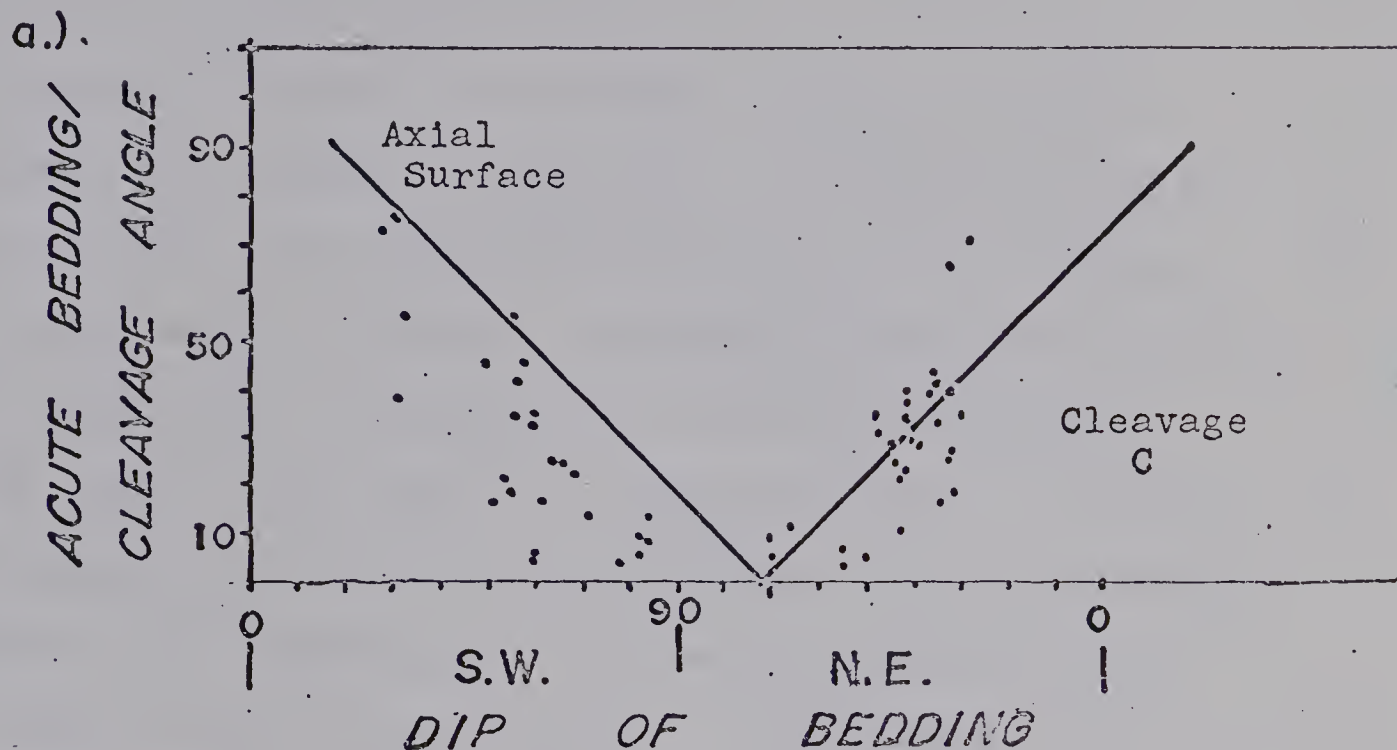
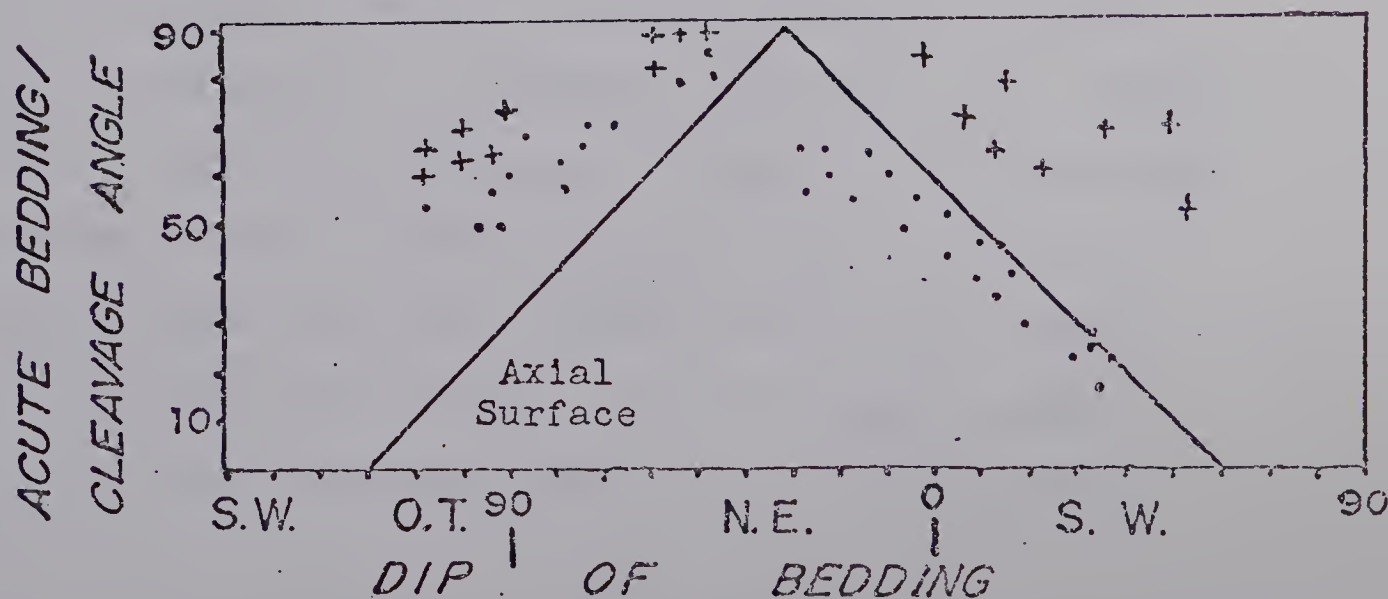


FIGURE 15

Cleavage A (.) and Cleavage D (+) in the Muhigan Creek Anticline. Measurements were taken in Old Fort Point strata in the core of the structure. Note the similarity between Cleavage A here and in the Jasper Anticlinorium (Figure 6).





sense as it is mesoscopically; offsets of up to 5 mm, and occurring along  $S_C$  planes spaced from 3 to 15 mm apart, are the general rule along such bedding laminations.

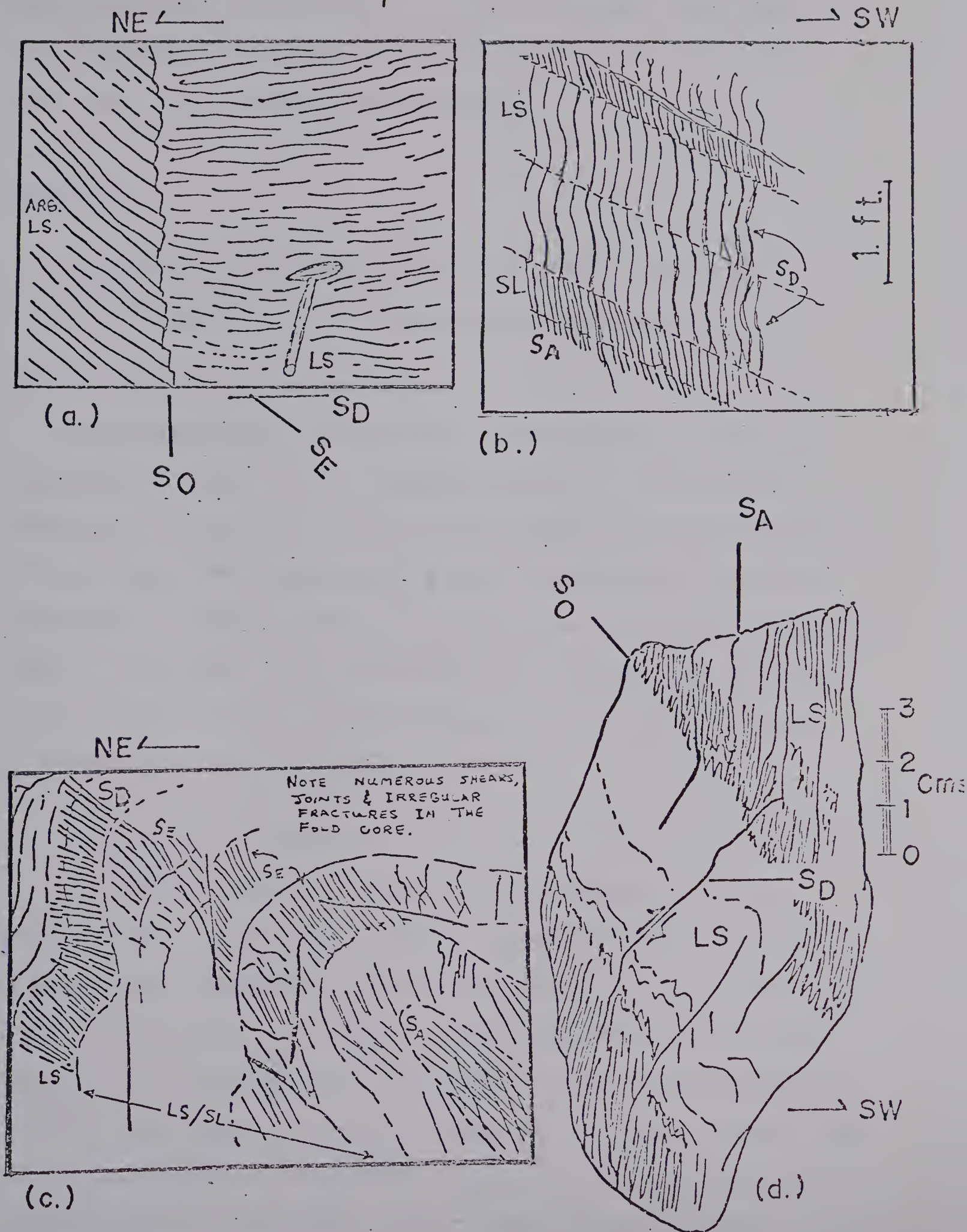
c) Tentative Working Hypothesis--

Cleavage C appears to be either a poorly fanned Cleavage B or a variety of Cleavage A occurring in coarser textured rocks. As suggested by the orientation models given in an earlier section, the angular differences between a true axial plane foliation and a foliation normal to bedding would be very small in the axial regions of folds. This behavior would be accentuated by the observed shearing in either case, rendering it difficult or impossible to decide whether one is dealing with a distinctive type of cleavage or with a Cleavage B in which late shearing and internal rotation of inter-cleavage domains have further modified the internal fabric.

We must consider, however, that Cleavage C, by definition, comprises discrete surfaces of kinematic discontinuity. An example considered below (Figure 27) illustrates a bedding contact at which Cleavage A is cut by a set of such planes of kinematic discontinuity. These planes cut spectral type Cleavage A (Branch 2) at low angles and pass upward into a pebbly sandstone with little or no deflection so that the planes closely parallel the axial surface of the mesoscopic fold. In this example, these planes, along which shearing effects are quite apparent,



FIGURE 16: Mesoscopic Relations



Muhigan Creek anticline — Old Fort Point formation.



bisect the typical Cleavage A/Cleavage B intersection angle found elsewhere in the fold. It is therefore concluded that Cleavage C has quite properly been differentiated as a distinct type by Charlesworth et al.

#### Cleavage D

Cleavage D is common in Old Fort Point limestones of the Meadow Creek and Muhigan Creek Anticlinoria.

##### a) Mesoscopic Description--

The orientation of Cleavage D is identical to that of Cleavage B (Figure 15 cf. Figures 12, 13). It further resembles Cleavage B in that it is gradational with Cleavage A occurring in the calcareous slates interbedded with the limestones. Mesoscopically,  $S_D$  surfaces are smooth, generally 5 mm or less apart, and veneered with a coating of muscovite and chlorite. Some typical examples of  $S_D$  are illustrated in Figures 17a and 16b and d.

##### b) Microscopic Description--

In thin-sections cut parallel to cleavage, chlorite and muscovite marking the cleavage plane are very prominent, appearing as irregular patches and streaks, or as ellipsoidal books up to 0.5 mm in length. Micaceous minerals are also prominent in thin-sections cut normal to the bedding/cleavage intersection; most books are ellipsoidal in shape, their long axes lying parallel to parting planes which appear in such thin-sections as irregular, often discontinuous planes. In thin-sections sub-parallel to bedding, micaceous minerals



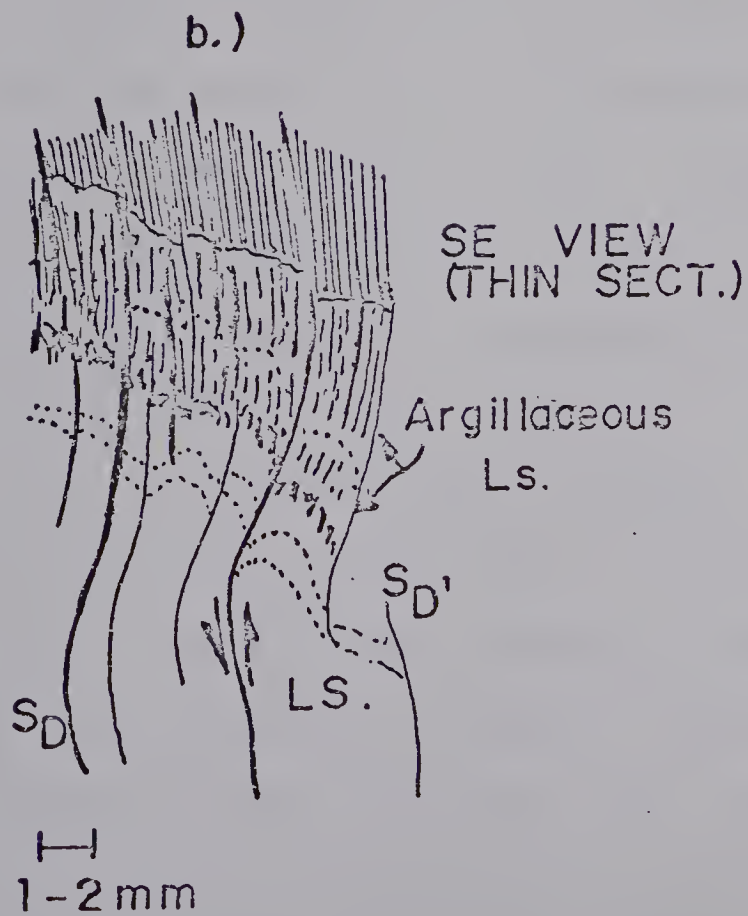
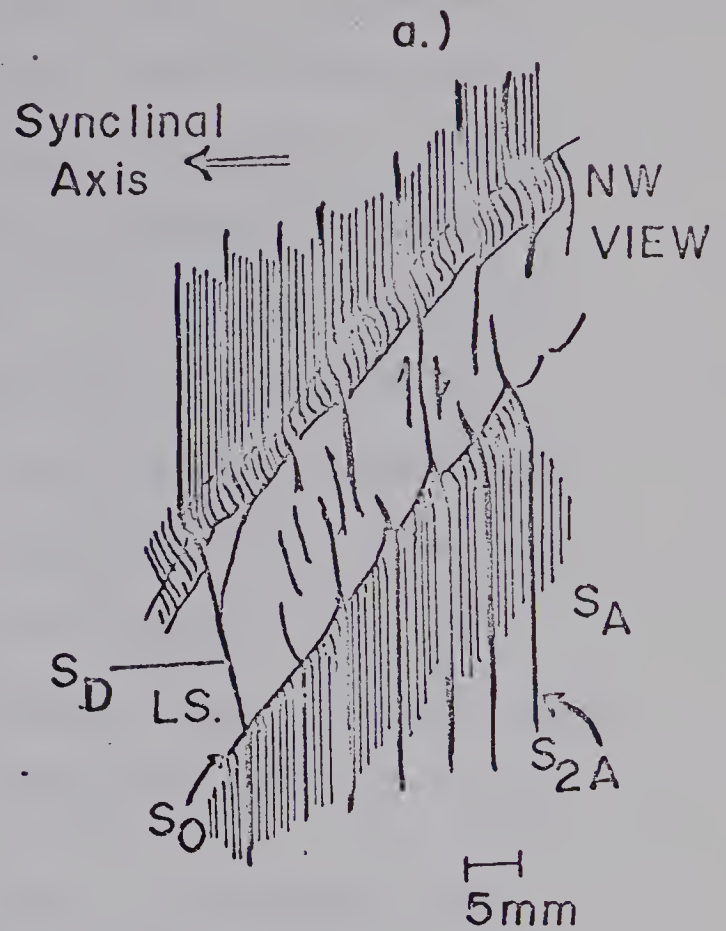
are not nearly as prominent; chlorite and muscovite books show up under medium power as extremely thin, discontinuous patches, usually trending parallel to  $S_D$  planes, though there are occasional, near-round ellipsoids of about 0.05 mm diameter.

Most  $S_D$ -surfaces are simple in nature, consisting of irregularly spaced, wavy-traced planes which may be either parallel or anastomosing. Granular calcareous material between  $S_D$  planes is elongated parallel to the cleavage, especially in thin-sections normal to the bedding/cleavage intersection. Thin-sections with the latter orientation, where argillaceous content is high, show a greater number of  $S_D$  planes per millimetre (4-7) than nearby clean, homogeneously coarser material (0.2 - 0.6 per mm); the 'extra'  $S_D$  planes simply disappear at the boundary between the two lithologies, although occasionally some of the closer spaced planes may penetrate as much as several millimetres into the clean limestone (Figure 17a, b).  $S_D$  planes which pass into the coarse material are invariably deflected toward the bedding normal by an angle roughly equal to the acute angle between cleavage in the 'dirty' material and bedding. Such behavior is not common with any of the other types of cleavage. Usually the contact zone is a zone of penetration along which the finer grained material between the wider-spaced  $S_D$  planes has been displaced upward in a manner resembling the 'intrusion' of



FIGURE 17 Cleavage D— Old Fort Point formation.

Samples shown are  
from  
Muhigan Creek  
Anticlinorium





argillaceous material into sandstone where Cleavage A passes into Cleavage B (see dovetail sutures below and Figure 17b). The  $S_D$  planes of the limestone may pass through the limestone after initial deflection or die out along their trend and be replaced en echelon by another plane 1-3 mm up-dip (Figure 17a). In the last instance, the sub-parallel replacement plane may either die out itself or pass through to the upper boundary of the bed. In either case,  $S_D$  makes essentially the same angle with bedding at both the base and top of a unit, since the cleavage planes are deflected through about the same angle but in the opposite sense when leaving as when entering.

Alternatively, for example where a limestone bed is several inches thick,  $S_D$  planes about 5 to 7 mm apart may be seen to steepen rapidly beyond the base of the limestone until the plane makes an angle of 45 to 60 degrees with bedding, but dipping in the opposite sense. Beyond the lower 1/3 to 1/2 of a bed these planes begin to 'flatten' by gradually moving back toward the orientation they had upon first entering the bed. This behavior is similar to that of cleavage mullions as described by Weiner (1966) but the lenticular 'mullions' formed here do not become separated from the rest of the unit although, where bedding is steep, some of these 'blocks' may become offset along  $S_D$  in a fashion similar to that associated with Cleavage E. That is, the curved version of Cleavage D may be modified by 'normal-fault' movement on normal (southwest) limbs of



folds and 'reverse-fault' movement on overturned limbs. The curvature of  $S_D$  is also reminiscent of the curvature of  $S_B$  in graded competent arenites.

In some cases beds several inches thick may contain both curved  $S_D$  and the types described earlier. In these circumstances, the curved type is the least penetrative and will occur only at intervals ranging from 0.5 to 1.0 times the thickness of the bed. If both types occur in the same bed the curved type will always be associated with displacements and the other will not.

c) Tentative Working Hypothesis--

En echelon dying out of  $S_D$  planes may be related to what Dahlstrom and others have referred to as 'structural transference' when encountered on a regional scale. In these limestones, however, grain size is quite uniform and there is a general lack of closely spaced S-surfaces other than the discontinuities along grain boundaries. Since the limestones show a preferred orientation of elongated grains parallel to the cleavage, grain boundaries parallel to the long dimension of the grains define statistical S-surfaces along which the grain fabric has been aligned. Discontinuous  $S_D$  surfaces, however, show displacement and may contain some splinters of recrystallized quartz near silty bands, long calcite grains, or micaceous minerals; thus they are real, planar, and marked by kinematic discontinuity and minor recrystallization. In thin-sections



and in many polished sections, it can be seen that flowage parallel to a given  $S_D$  plane decreases in magnitude in a stratigraphically upward direction until only the planar discontinuity itself, without evident displacement, is present. En echelon to those portions of an  $S_D$  plane along which active transfer of material has ceased will be another  $S_D$  plane along which active transfer does take place at about the same structural elevation as the dying out in the first plane. Since the hingeward sides of  $S_D$  domains always move away from the limbs as the bed is folded, material lying to hingeward of any given  $S_D$  plane must always be either stratigraphically higher or lower than the material along the terminal parts of the given  $S_D$  plane. The net result is that  $S_D$  planes of both the continuous and en echelon types will tend to migrate hingeward. Resolution of local stress patterns would undoubtedly resemble those on a map view of a wrench fault, in which tension and compression quadrants are shown. Again, there is little likelihood that any of the structures related to Cleavage D are tensional since there has been translation (shear), bed thickening (dilatation plus change in shape), and because the tails of the curvilinear  $S_D$  planes point in the opposite sense to those expected under tensile conditions.

#### Cleavage E:

Cleavage E occurs in Old Fort Point limestones and slates of the Meadow Creek Anticlinorium and in siltstones in old Fort Point strata on the Jasper Anticlinorium.



a) Mesoscopic Description--

Cleavage E is always symmetrically distributed about the axial surfaces of folds (Figures 18, 19).  $S_E$  surfaces are flat to recurved, and separate tabular domains from 5 to 20 mm wide in which original bedding has been folded. The best examples are found in tightly folded limestone and slate beds of the Old Fort Point Formation across the central zone of the Meadow Creek Anticlinorium; here,  $S_E$  planes parallel the axial surfaces of folds (Figure 41). Slickenside lineation is often present normal to the fold hinges. Sense of displacement, as in the case of Cleavage C, is such that the axial regions of antiforms have moved upward while synclinal hinges have moved downward relative to the limbs. Figures 18 and 41 summarize relations between Cleavage E and other features as observed on the Meadow Creek Anticlinorium.

Cleavage E also occurs in Member B siltstones of the Old Fort Point Formation along the Jasper Anticlinorium. Evans (1961) reported that bedding laminations on either side of  $S_E$ -surfaces may be displaced, in some cases these laminations being sharply flexed near planes which show little or no displacement. As shown by Figure 19a and b,  $S_E$  attitude here depends on the attitude of bedding. Figure 20 illustrates outcrop appearance and relations.



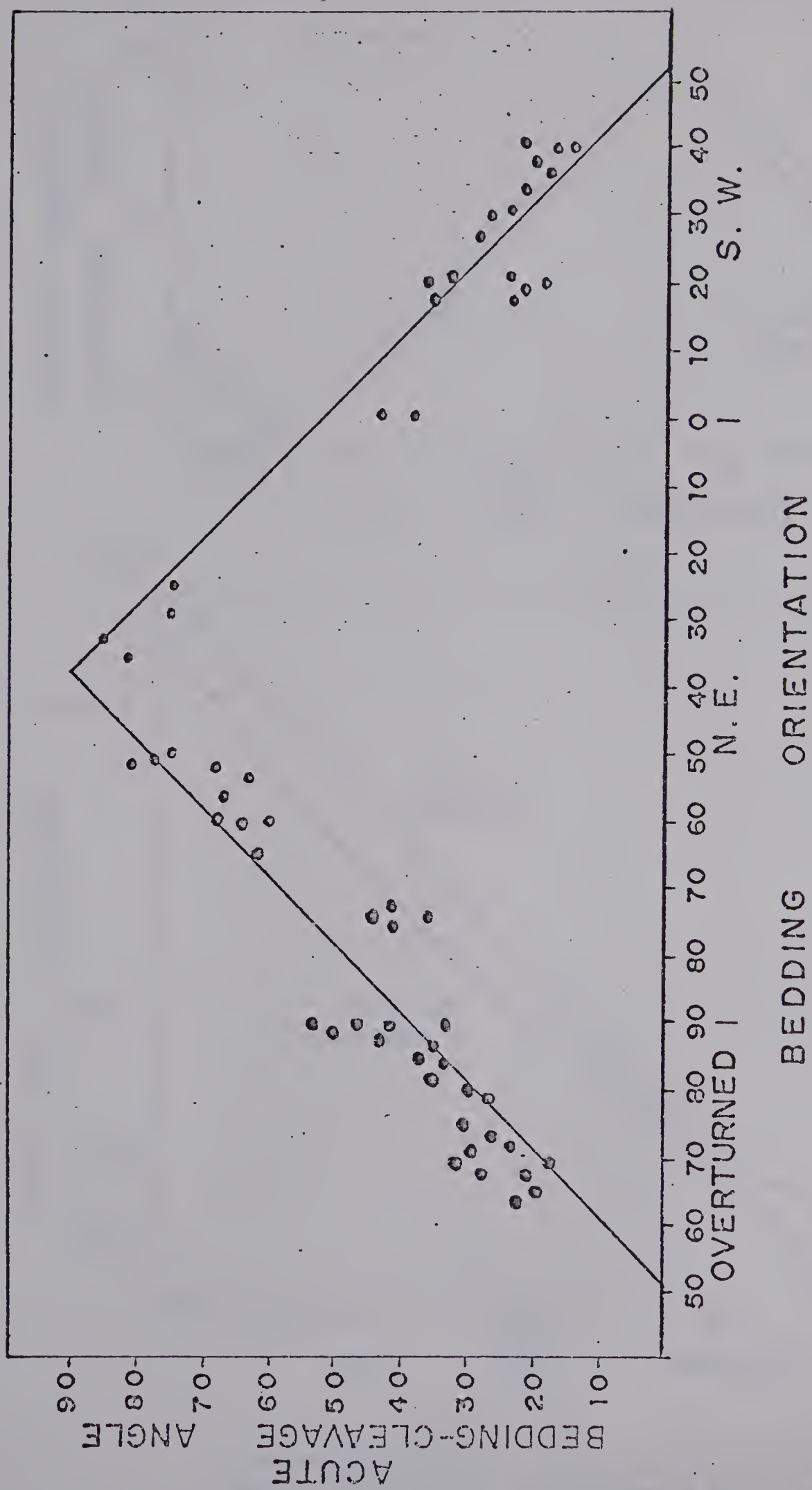
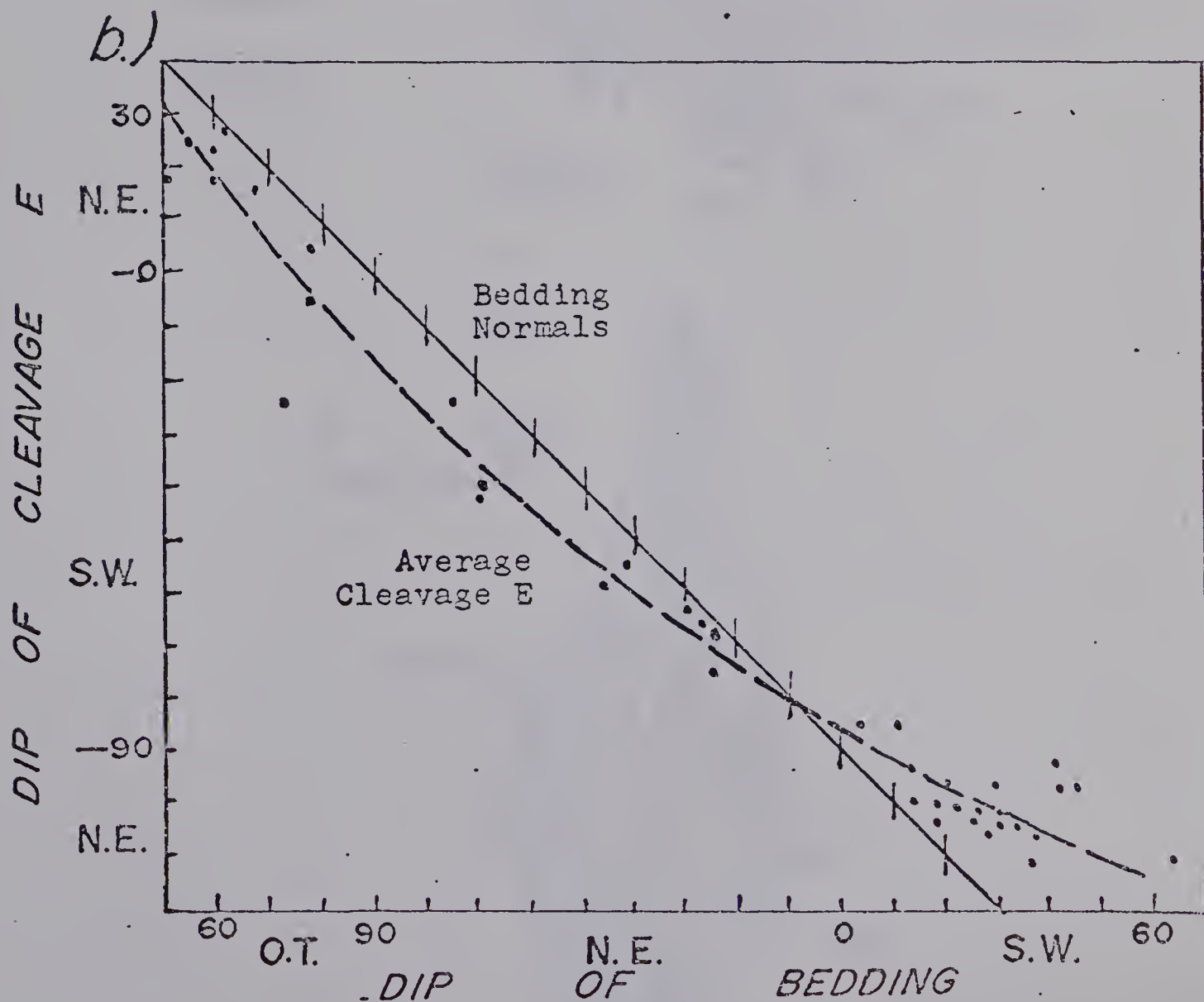
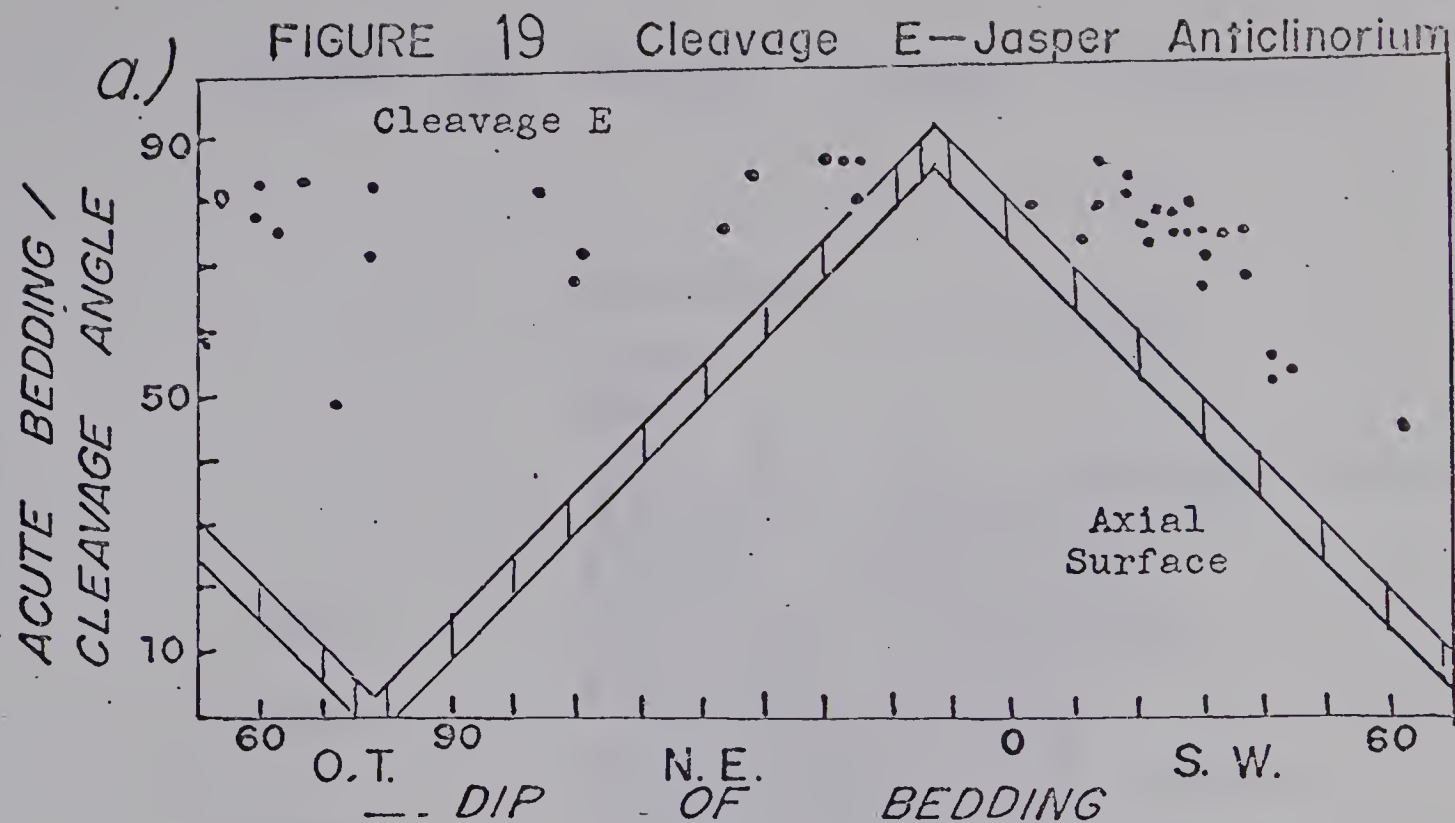


FIGURE 18 Cleavage E. Meadow Creek anticlinorium.

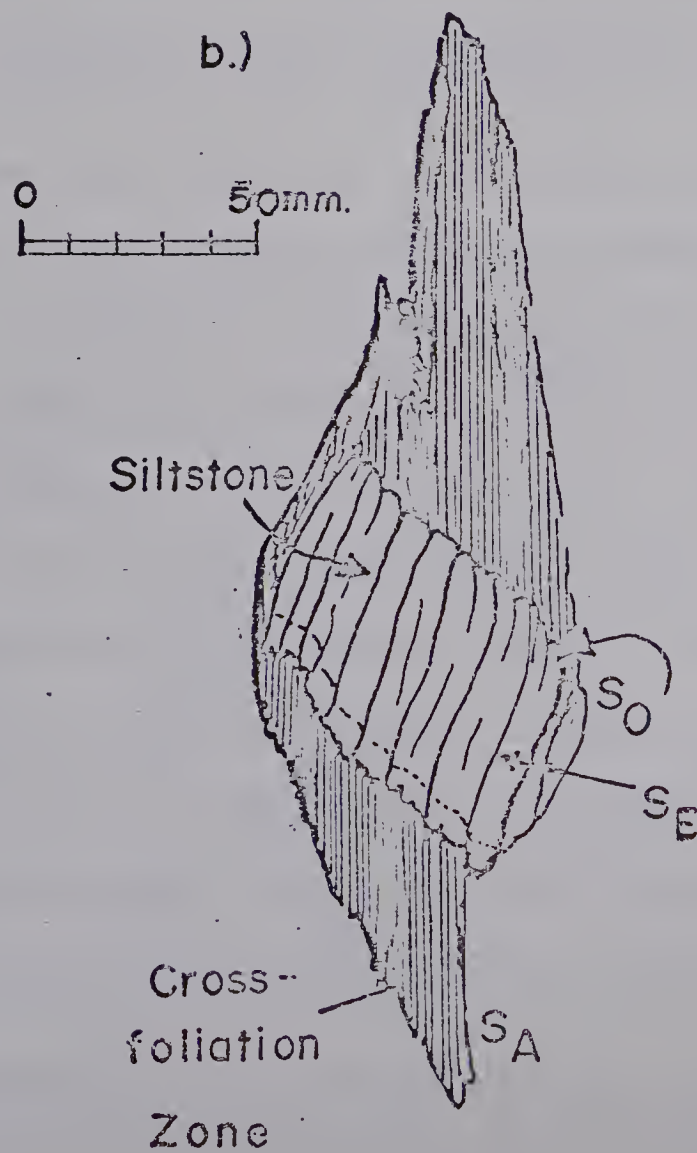
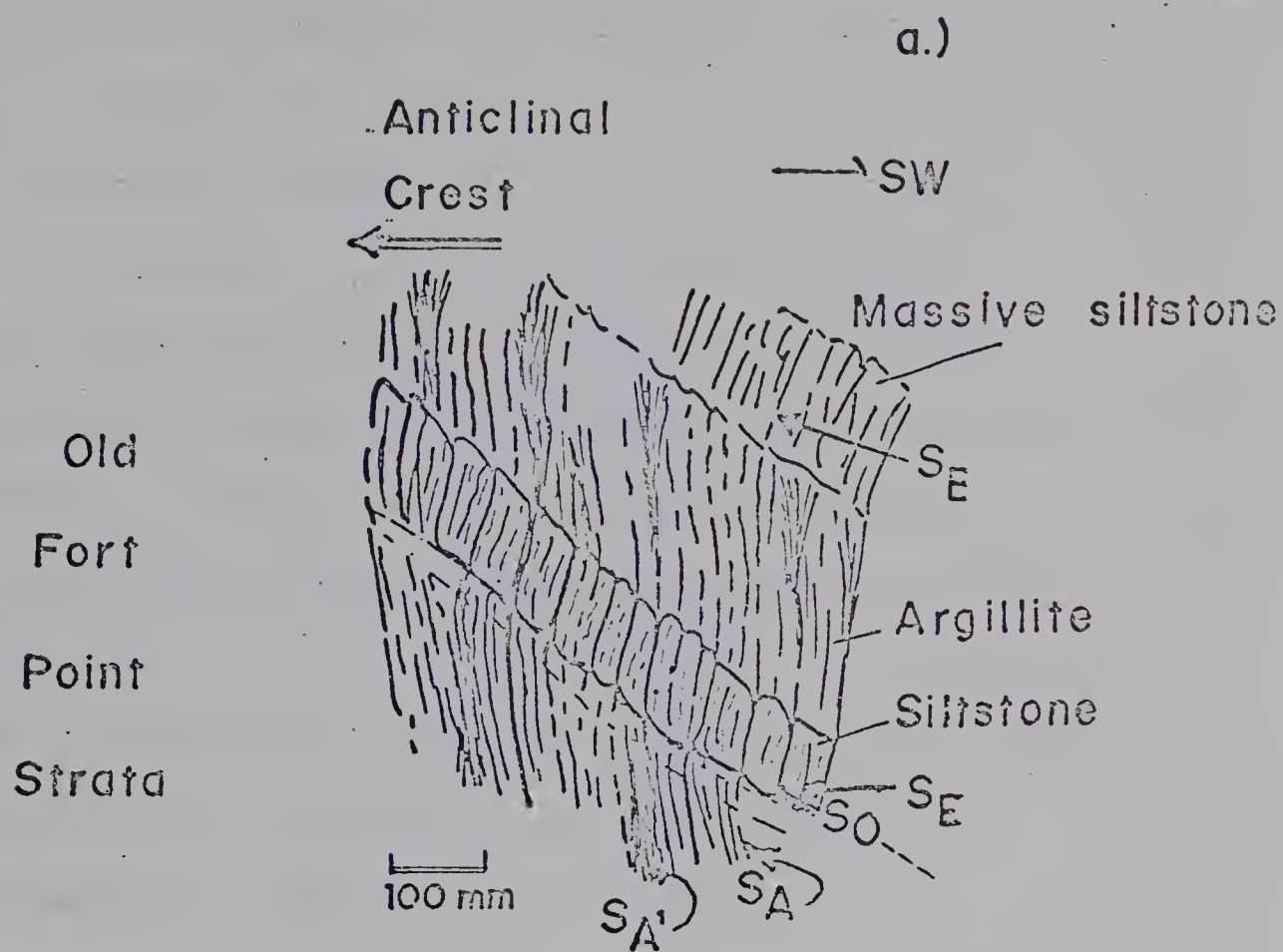




Comparison between (a) attitude of Cleavage E versus the axial surface and (b) cleavage attitude versus the bedding-normal in Old Fort Point siltstones of the Jasper Anticlinorium. (Information collected by Evans, 1961).



FIGURE 20 Cleavage E—Jasper Anticlinorium





b) Microscopic Description--

In thin-section  $S_E$  planes are irregular, often discontinuous, and flat 'S' shaped so that variation of up to  $\pm 35$  degrees off a mean plane in a space of 2.5 to 3 mm are not uncommon. Even in relatively clean limestone beds, where mesoscopic  $S_E$  appears to be knife-sharp or nearly so, microscopic examination usually shows that  $S_E$  'planes' are indeed narrow zones consisting of numerous closely spaced, discontinuous planes along which coarse 'gouge' like material is concentrated. Such material is usually iron-stained and composed largely of brecciated quartzose and micaceous material, the latter being more abundant than quartz. Muscovite and chlorite books, generally less than 0.5 mm in length, are usually interleaved and bent, sometimes appearing frayed and broken.

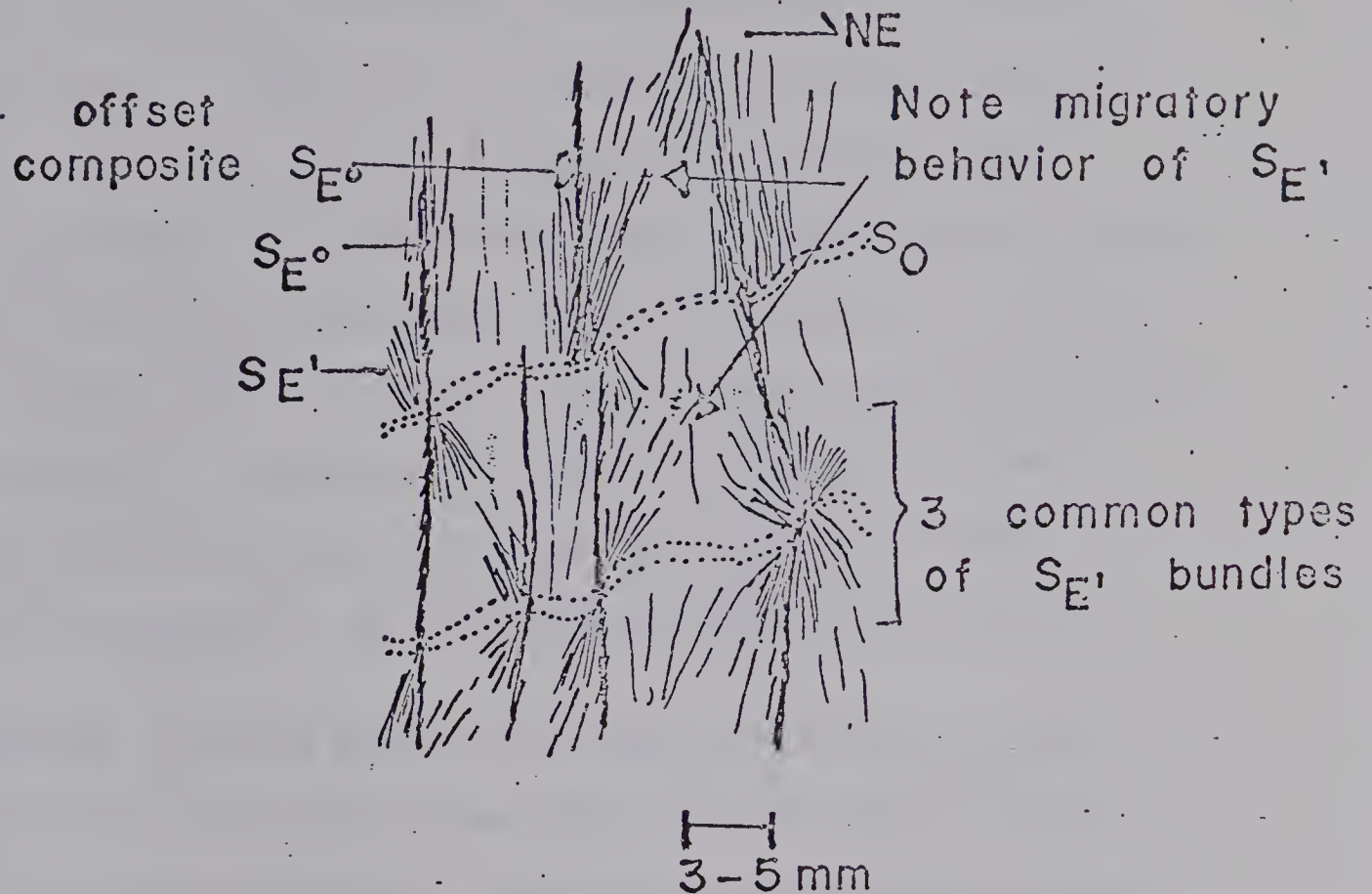
Domains between  $S_E$  planes are 5 to 15 mm thick. In these, bedding has been strongly disrupted into folds and crumples. Such crumpling is most evident in the slates but occurs on a less spectacular scale in the limestones as well. Micaceous minerals in the slate tend to parallel the  $S_E$  planes. These planes pass through both host lithologies with only minor deviations from a mean plane. Domains on opposite sides of  $S_E$  planes are offset so that those domains on the side nearer to an axial region have moved away from the limbs. 'Stratigraphic throw' of these displacements ranges from less than 5 mm to more than one centimeter.

Preferred orientation of material in and adjacent to

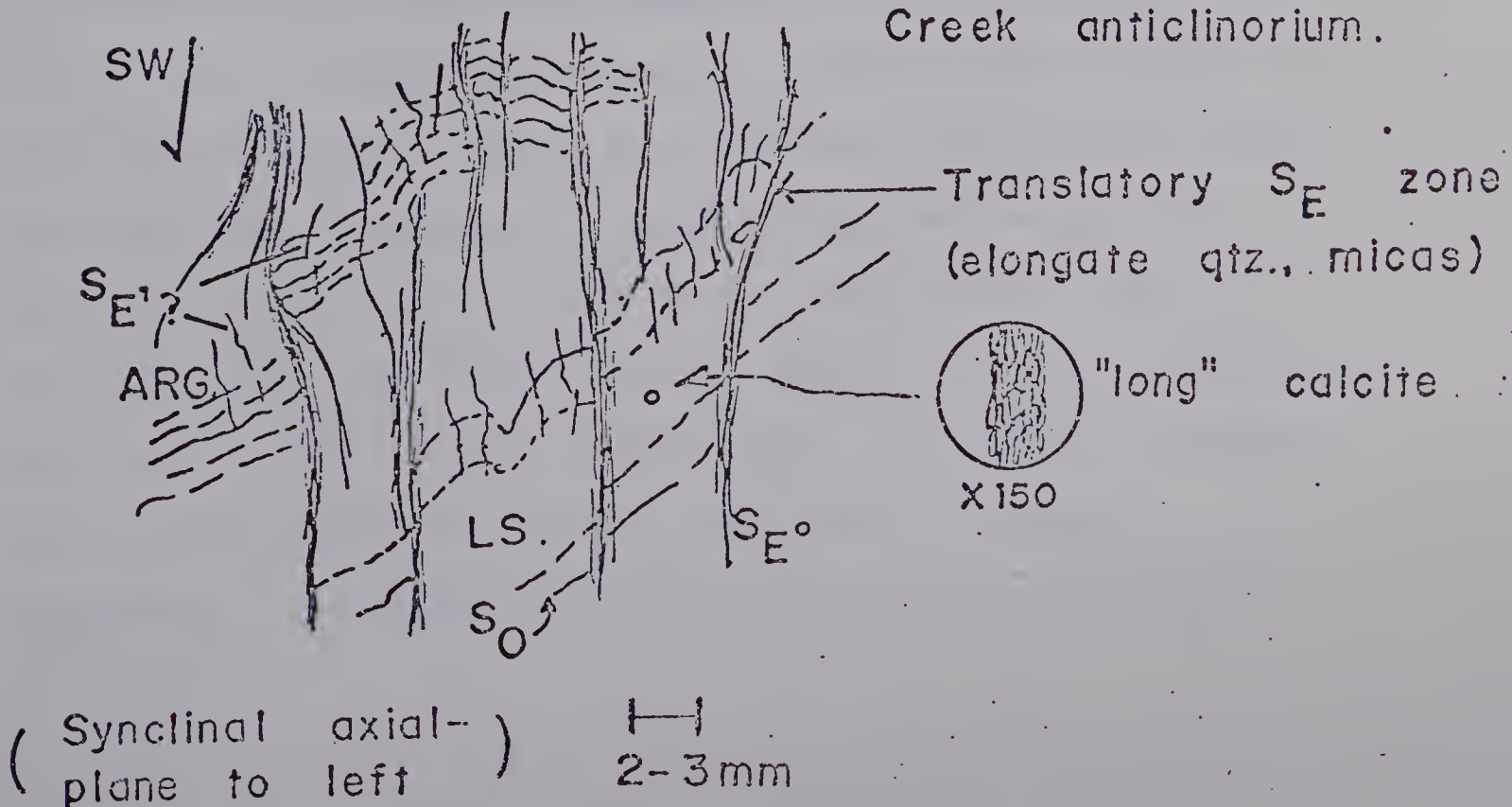


FIGURE 21: Cleavage E—Microscopic views

a.) Member B siltstone at Old Fort Point.



b.) Member B limestone and argillite from a reclined syncline — central zone, Meadow Creek anticlinorium.





$S_E$  planes is commonplace. Blade-like quartz, with length to width ratios ranging from 3:1 to 10:1 always lies sub-parallel to  $S_E$  in thin-sections cut normal to sub-normal to the bedding/cleavage intersection; such quartz is almost invariably optically continuous throughout and is usually inclusion-free. Extinction in these long quartz grains inclines at 10 - 20 degrees (average 14 degrees) to an average  $S_E$  plane. Occasionally small twinned quartz grains also occur along the cleavage, their twin plane ( $\cong$  c-axis) lying at about the same angle to  $S_E$  as the extinction zones in other grains. Calcareous grains in domains between  $S_E$  planes show a strong preferred orientation in thin sections cut normal to the bedding/cleavage intersection.

Cleavage E often penetrates small mesoscopic folds occurring in adjacent anticline and syncline pairs in the Meadow Creek anticlinorium; it is especially well developed where bedding is thin (Figure 28). Under such circumstances, or where the two lithologies occur as thin laminae, the  $S_E$  planes separate tabular domains in which numerous thin, short planes roughly sub-normal to bedding occur (Figure 21b). These discontinuous planes are irregular in trend and shape. They are best developed in calcilutites and rarely pass into the coarser material of silty bands; where such invasion does take place the fine planes terminate before appreciable penetration is achieved. In some sub-domains the discontinuous fine planes are present in great abundance. In terms of  $S_E$  their orientation is always irregular.



In siltstones of Member B of the Old Fort Point Formation along the Jasper anticlinorium spacing and nature of  $S_E$  is much the same as in the limestones and slates just discussed, but the thin intermediate planes are better developed. In most domains  $S_0$  has been warped into antiforms on the upwardly translated sides of domains and into synforms on the downthrown sides. Since  $S_E$  planes thus tend to bring an antiform on one side opposite a synform on the other, and since the fine, discontinuous planes occur normal to  $S_0$ , a bundling effect is produced in the vicinity of  $S_E$  (Figure 21a). In some sub-domains, behavior of the finer planes is such that they appear to converge upon the axial surfaces of the microscopic synforms, approaching from the convex side, but they diverge (fan) downward from the antiformal crest on the other side of the  $S_E$  plane. On the other side of  $S_0$  the opposite behavior holds. In addition, the fanning is asymmetrical in that the minor planes nearest  $S_E$  itself tend to parallel it. The fanning is therefore bilaterally symmetrical about both  $S_0$  and  $S_E$  so far as sense is concerned, but it is inequant and asymmetrical in its form and development.

In other sub-domains there is never any fanning of the minor planes on the intrados of microfolds, but fanning away from parallelism is prominent on the extrados side. This type may be overlain or underlain by the type described above. The occurrence of either type, or any combination of them will produce a pinch-and-swell effect



in the domains between  $S_E$  planes. In still other sub-domains an  $S_0$  contact may not be penetrated by minor planes at all within a given inter- $S_E$  domain, but when three adjacent domains are considered the one-sided pinch-and-swell structure on each side of the central domain will produce the same effect mesoscopically. The latter is probably the most common of the three, and can usually be identified in outcrop and polished section. In some thin-sections, especially where  $S_E$  is closely spaced (3 - 5 mm), these minor planes may be so well developed that it appears at first glance that there are two foliations, Cleavage E cutting the finer set.

c) Tentative Working Hypothesis--

While mesoscopic observation suggests that domains between  $S_E$  planes nearest an axial region of a fold have moved hingeward, the precise nature of displacements of  $S_0$  in individual domains is less regular and harder to describe. Most commonly, folded bedding in alternate slices is weakly asymmetrical in such a way as to suggest that domains have had their nearest-to-hinge side 'rotated' toward a crestal region while the opposite side of the domain has either 'moved' limbward or 'lagged' behind. Thus  $S_0$  laminae on the limbward side are attenuated and steeper dipping than those on the 'flatter-lying' crestal side. The attenuated limb of such crenulations commonly makes an angle of 15 to 25 degrees with  $S_E$  on the limbward side whereas the flat limb may make a crestward-opening



angle of anywhere between 90 and 120 degrees with the  $S_E$  plane on the up-limb side. In other cases the median portion of a domain appears to have been translated crestward relative to both sides of the domain; in this case trace bedding will make a crestward opening angle of 30 to 50 degrees with the  $S_E$  planes on either side of the slice.

# Lithological Contacts and Cleavage Inter-relations--

Charlesworth et al (1967) have already stated that on mesoscopic grounds, several of the above described cleavages are structurally and/or spatially related (Table II); this discussion would be incomplete without at least some description of such shared relationships and of major differences between the most commonly observed associations.

TABLE II      Classification of cleavage types studied in the Jasper area		
NATURE OF	GEOMETRY	
S -- SURFACE	One set of S-surfaces // to axial surfaces	One or more sets inclined to axial surface and to each other
Independent of planar preferred orientation of mineral grains. Mainly ruptural breaks or cracks.	Cleavage C in arenite and Cleavage E in limestones.	Cleavage E in siltstones.
Cleavage defined by planar preferred orientation of inequant minerals.	Cleavage A in slates (also grades into Cleavages B,D)	Cleavage B in coarse arenites; Cleavage D in limestones.
Cleavage associated with crenulation of pre-existing S-surfaces.	Modifications of Cleavages A, C, E.	Modifications of Cleavages A, C, E.



Since bedding is usually detectable in almost every reasonably good outcrop in the Jasper area, the writer has attempted to document some of these relationships by sampling and studying as many  $S_0$  contacts as were readily accessible.

#### Types of $S_0$ Contacts Observed

Broadly speaking, three types of bedding contact are commonly observed in the deformed rocks of the Miette Group at Jasper. In order of increasing utility for cleavage analysis, they are: 1) Discontinuous contacts, where a definite discontinuity exists between two adjacent lithologies; 2) gradational contacts, such as those in graded beds; and 3) 'welded' contacts, in which the contact between lithic units is tightly cemented, or where it is structurally 'sutured' over a zone with a stratigraphic amplitude of from about one millimetre to more than a foot, and there is no sharp plane of contact.

All three types, with occasional modifications, occur between lower Wynd slates in which Cleavage A is well developed and arenaceous units in which Cleavage B predominates or in which Cleavage C occurs. Contacts between Old Fort Point limestones and slates are usually of the welded type mesoscopically, though some of these are gradational on the microscopic level; thus, Cleavages A, D and E in the Old Fort Point strata of the Meadow Creek anticlinorium are most commonly associated with gradational



and welded contacts. Cleavages A and E, in Old Fort Point slates and siltstones of the Jasper anticline, are usually separated by discontinuous contacts, especially in the northeast limbs of folds; welded contacts can also occur, especially where bedding is thin.

#### Discontinuous Contacts:

In this class, the interstratal contact is a curvilinear or near-planar interface which is a surface of kinematic as well as lithological discontinuity. One example of this type was illustrated by Charlesworth and Evans (1962, Figure 3) who showed the extremities of Cleavage A planes in a relatively thin slate rotated toward the bedding normal near the contact with a competent siltstone containing Cleavage E as the result of slip along the contact. In addition, the siltstone has been broken into a crude block-mullion structure not unlike the key-stone arch of architecture and antiquity. Figure 8 is redrawn from Evans' original field photo of the small syncline from which this example is taken. Comparison with Figure 7 (after Charlesworth and Evans, 1962) shows that there has also been rotation of these mullions in the crestal region. The angle of rotation is comparable in magnitude and sense to that illustrated by the smaller scale cleavage-boudinage, and nearly identical in magnitude to the angle between actual Cleavage A poles in the slate and 'ideal' cleavage poles predicted for homogeneous slates where the effect of competent material would be nil. The deviation of Cleavage A in this tight syncline



could thus be due to a buckling of  $S_A$  surfaces as the result of clockwise rotation of the mullions, plus a tendency for blocks of the crestal area of the syncline to move downward relative to those of the limbs. Similarly, in relatively thin slates, crestal thickening as the result of shearing along  $S_A$  might be expected to cause a convergence crestward as the cleavage planes pass into the high-stress region of the intrados. The combined effects of such late affine movements by simple shear plus the element of internal rotation resulting in rucking of  $S_A$  and rotation of competent blocks would together favor slip along the contact between the two lithologies. That such movements have taken place is evidenced by the commonly observed slickensides on both  $S_0$  and  $S_A$  trending normal to the fold hinges. Evidence of earlier movements along  $S_0$  due to buckle folding itself would tend to be destroyed by the later internal movements, much as Stauffer (1962) has suggested. For this reason, such contacts can only be imperfectly interpreted and are of but limited usefulness in cleavage analysis.

Slickensides and rucking effects can also be found in the Minaga Creek synclinorium, especially in outcrops of Wynd conglomerates and slates along the new highway. In the Miette River fold (see below) there are slickensides, possible small feather joints, and kink folds along this type of contact between a thick Wynd slate and a pebbly sandstone.



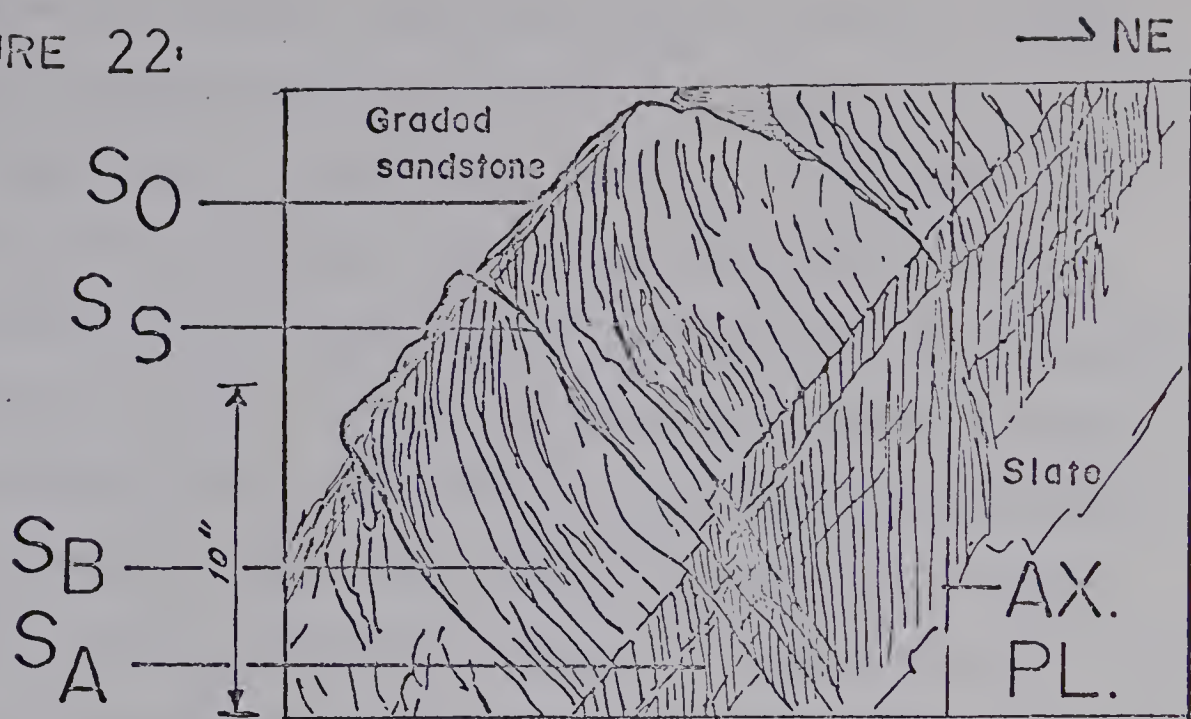
Gradational Contacts:

Gradational contacts here include: a) continuously graded beds, where the particle size in a lithological unit shows progressive fining upwards; b) types of discontinuous or interrupted graded bedding, such as (1) where a coarse bed grades upward into a comparably finer material that quickly passes upwards into another coarse-grained zone which again grades into fine material; or (2) where graded arenite 'pods', such as lenticular channel sands or truncated bgraded beds, are enclosed in a thick jacket of slate in which Cleavage A is well developed.

(a) Continuous Graded Bedding: Figure 22 illustrates an arenite bed about ten inches thick overlying a slate unit of comparable thickness in Wynd strata on the southwest limb of the Huhigan Creek anticline north of the Miette River. Cleavage A in the slate is considered to be an axial plane cleavage, and makes an angle of 38 to 40 degrees with bedding. A close-spaced  $S_{1A}$  and an  $S_{2A}$  with a spacing of 3 - 5 mm are present in the slate. The upper contact of the slate is 'welded' to the arenite so that there has been no bedding-plane slip. The  $S_{2A}$  surfaces cross the lithological boundary without pause, but within the first two inches their trend deviates 12 to 32 degrees in the direction of the bedding normal, while the coarse grain fraction decreases from 4 - 7 mm to 1.5 - 3 mm. Beyond this point grading is very gradual until near the top of the bed it becomes a clean silty argillite. To about the mid-point of the thin bed  $S_{1B=2A}$  planes are sub-parallel

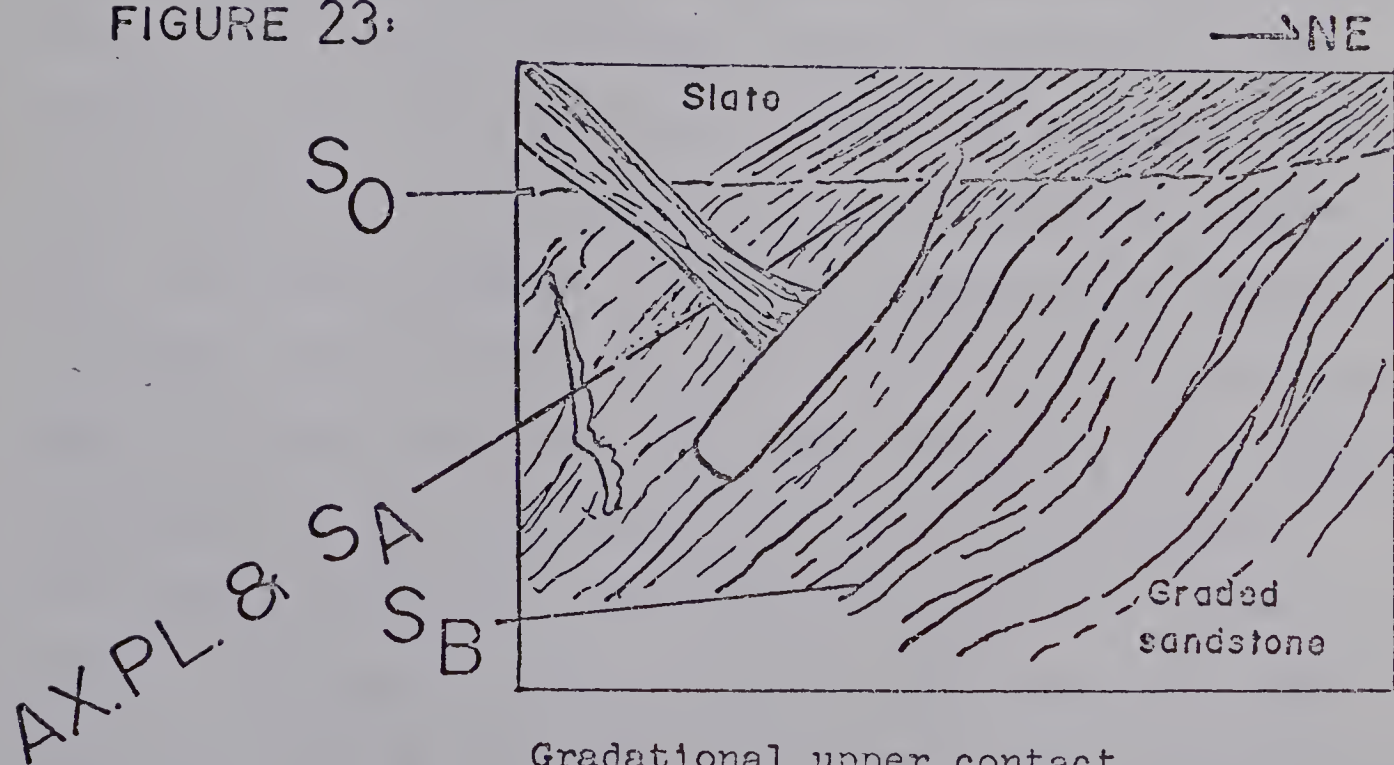


FIGURE 22:



Graded bedding above a cemented contact

FIGURE 23:



Gradational upper contact

Southwest limb, Muhigan Creek anticline—Wynd fm.



and marked at 0.5 to 1 inch intervals by an  $S_{2B}$  parting; near the midpoint these  $S_B$  planes all define a mean plane which more or less parallels  $S_A$  in the slate, but step-outs of less than a foot in either an up-limb or down-limb direction find  $S_{1B}$  inclining at up to 10 degrees to mean  $S_A$  so that the  $S_B$  foliations are fanned irregularly upwards at mid-bed. Beyond the middle of the bed all  $S_B$  foliations converge upward so that in the uppermost inch of the unit both spacing and attitude are identical with those of  $S_A$ . The sharp deviation at the base and the convergence of cleavage near the top of the graded bed are typical of the behavior of cleavage in thicker units as well.

Comparison of Figures 7 and 22 also shows that there is a similarity between the block mullion structure cited earlier and the late movements which took place in this example. Here, both the argillite and the graded arenite are cut at 8 to 10 inch intervals by sub-parallel shears ( $S_S$ ) which make an angle of 40 - 45 degrees with the mean  $S_A$  plane, and fan about the axial surface. Since the above angle is almost identical with that between  $S_A$  and bedding. Cleavage A is the acute bisectrix of the  $S_0$ - $S_S$  planes. The same relationships, including the angles, are true for the Charlesworth-Evans example. There has been some movement along  $S_S$  such that the up-limb blocks have slid 1 to 2 inches up and away from the axial-surface of the fold. In effect, there has been a counter-clockwise 'bending' of  $S_0$  in the southwest limb of the Muhigan Creek



anticline when viewed looking north-northwest. The mechanism is similar to the keystone-arch effect in Evans' syncline, though rotation of individual blocks about an axis parallel to the fold hinge does not seem to have taken place. If the average limb length is taken as about 300 feet and used as a radius of bending, then an average incremental slip of 1.5 inches taken at 1 foot intervals gives a total counter-clockwise rotation of 7 degrees. Using a maximum incremental slip of 2 inches would increase this to 9.5 degrees. Presumably such bending came late in fold history since the shear planes cut both  $S_A$  and  $S_B$ .

(b) Discontinuous Graded Bedding:

(1) Repeated or Interrupted Graded Beds: This example occurs in the southwest limb, near the core, in the Miette River anticline, (Figure 37, Unit A). It is believed that the uppermost graded interval was deposited after partial truncation of the lower graded sequence. Thin slates overlies and underlies the two-fold graded bed which itself is 5 to 6 feet thick.  $S_A$  in the underlying slate dips steeply southwest while bedding dips at 53 degrees southwest.  $S_B$  at the base of the lower graded bed is a wide-spaced (5-8 mm) cleavage which dips 40 degrees northeast, an angular deviation off mean  $S_A$  of about 45 degrees. The inclination of  $S_B$  increases upwards so that one foot above the base cleavage dips 40-42 degrees northeast, and near the base of the upper graded sequence it attains a dip of nearly 56 degrees. At this point, Cleavage A of the underlying slate is again the acute bisectrix of the bedding/ $S_B$  angle. There is no  $S_S$  plane here however, and  $S_B$  has gone

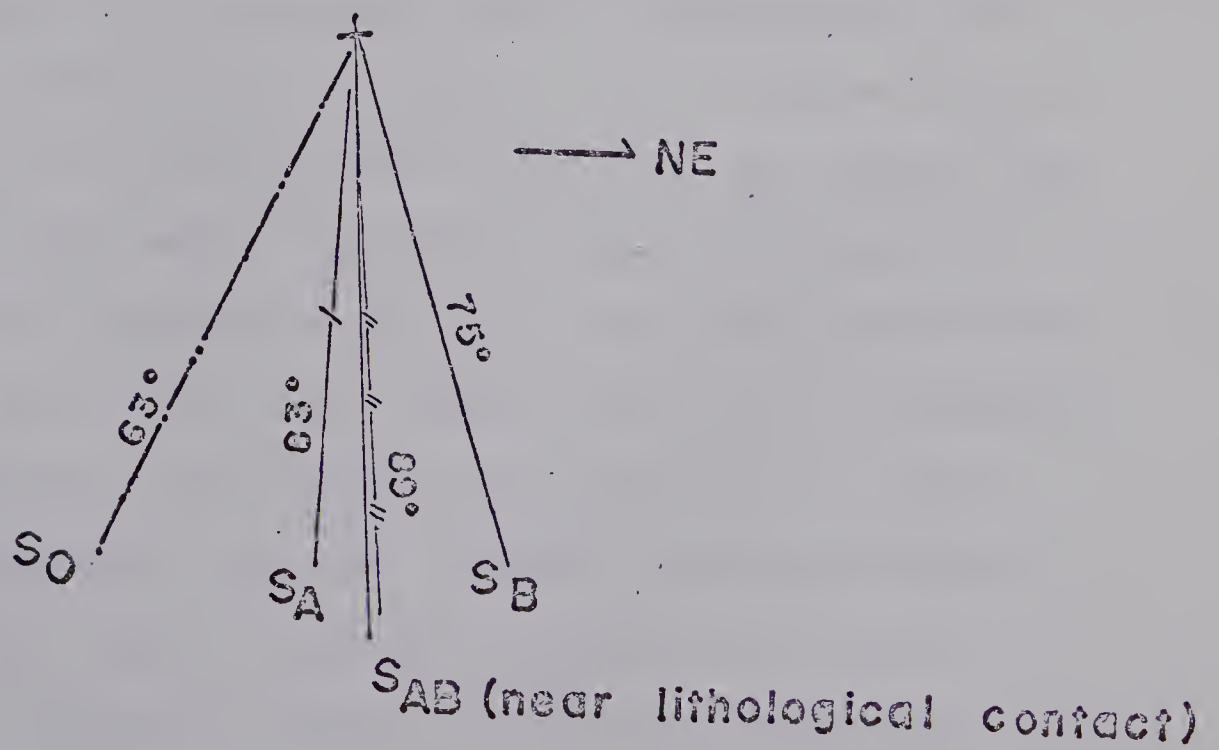
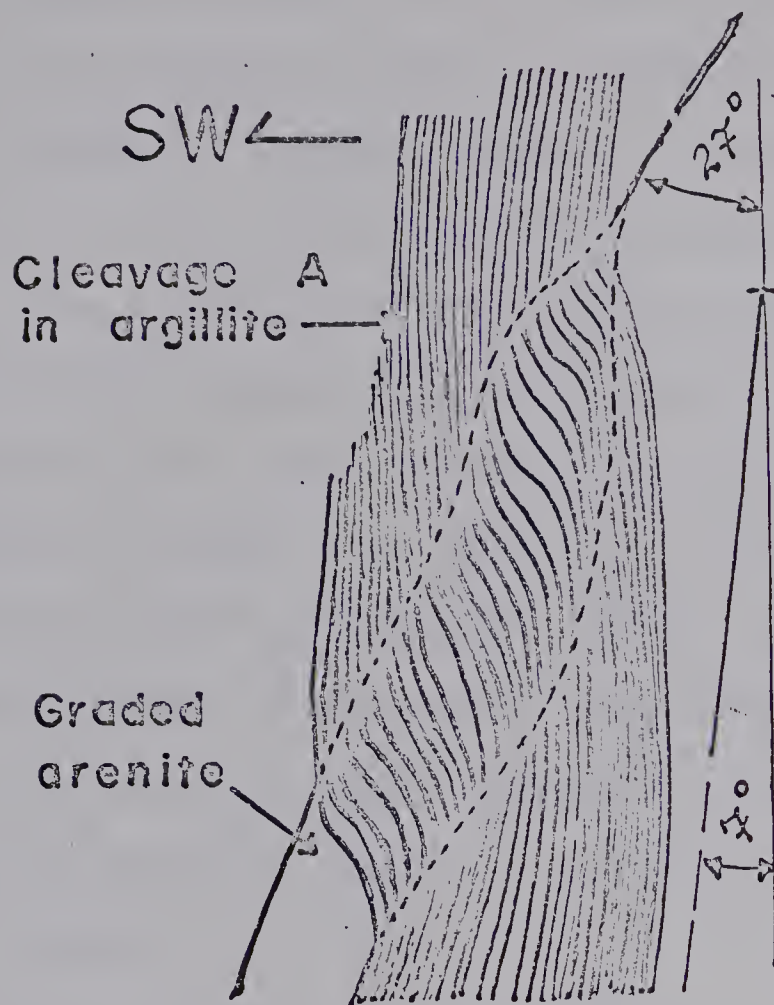


somewhat beyond the bedding normal on its path of deviation. As  $S_B$  passes into the coarse material at the base of the upper graded sequence it is again deflected in the direction of the bedding normal, this time in the opposite direction, so that its attitude is again 40-44 degrees northeast. Beyond this point the curvature of cleavage planes is smooth and there is perhaps a bit of convergence upward. Whether the odd behavior of  $S_B$  near the base of the upper graded bed is related to the mechanism of cleavage formation or whether it is related only to the swale-like nature of the lower boundary of the upper graded bed is debatable. Intuitively, one might expect that since both  $S_A$  and  $S_B$  show a tendency to converge on areas of high stress they should, conversely, diverge in the vicinity of a convexity or toward the vicinity of the neutral surface of the folded layer. Weiner's modified diagram from Bell and Currie (1964) showing the distribution of maximum shear trajectories in a competent bed which is being folded (Weiner, 1966, Figure 39) rather vaguely suggests something of this nature. It is worth noting, perhaps, that there was a hint of divergence at mid-bed in the previous example as well.

(2) Cleavage near an Arenite 'Pod': Along the railroad right-of-way near the axis of the Minaga Creek synclorium there is, enclosed in a thick slate bed, a graded lenticular channel sand (Figure 24). A typical Cleavage A is present in the Wynd slates, but unlike the behavior reported by Charlesworth et al (1967) this Cleavage A is not deflected around the competent material. Instead, as the lower



FIGURE 24: Cleavage in an arenite "pod"—  
lower Wynd formation.





boundary of the arenite is approached  $S_A$  steepens from 85-87 degrees southwest to vertical, then overturns to 89 degrees northeast within an inch-wide zone at the base of the arenite. Cleavage planes in the arenite also spread out in this zone so that they are some 2-5 mm apart. The attitude of these planes continues to flatten so that in the median zone their dip is 75 degrees northeast; since trace bedding dips about 70 degrees southwest, Cleavage A is almost in the position of acute bisectrix of the  $S_0$ - $S_B$  angle. In the upper half of the 'pod' deviations of comparable magnitude and opposite sense take place so that Cleavage A above the 'pod' again dips about 87 degrees southwest, ranging as low as 83 degrees.

Clearly, this case shares certain characteristics with both of the previous examples, yet is rather unlike either. If it is assumed that the top of the channel was essentially flat before folding and the development of cleavage, the irregular bottom and convex top visible near the uplimb end of the 'pod' (Figure 24) could be explained as the result of upward shear along Cleavage A. Such shearing would have produced a slight counterclockwise tilting of the 'pod', causing a steepening of dip on the order of perhaps 5 degrees; this would mean that Cleavage B could have begun to form when Cleavage A was the acute bisectrix of the shear/bedding angle as suggested by the earlier examples. Because of contemporaneous tilting, deflection of Cleavage B toward the bedding normal



did not increase as markedly as it did in the case just above, nor did it increase as rapidly as in the first case. The result of this interplay is an  $S_B$  which is S-shaped and shows less tendency to divergence and convergence than earlier examples.

### Welded Contacts

Included here are not only tightly cemented contacts, but 'sutured' contacts. There is no surface of kinematic discontinuity along either of these, and the lithological discontinuity itself is a zone within which the properties of the two lithologies not only meet but interlock. Since this zone can range from a fraction of a millimetre to a foot or more in thickness, such contacts are the most profitably studied of all from the standpoint of cleavage relationships.

Two principal variations are common in the Jasper area: (a) the planar type, in which the contact is usually sharp (a millimetre or less in width), tightly cemented, and has not been greatly disturbed since deposition so that it is sub-parallel to  $S_0$  in at least one of the adjoining beds; (b) a second type which may be designated irregular or dovetailed sutured contacts, in which there are small irregularities or projections along the contact such that two lithic units with different structural and physical properties are dovetail-joined as a consequence of primary causes, deformation, or both. Dovetail sutures



can occur on one or more scales ranging from less than a millimetre to several feet across. Larger examples usually include several kinds of microscopic sutures; mesoscopic sutures of the load-cast type are especially prominent in lower Wynd strata on both limbs of the Meadow Creek anticlinorium, and in several areas along the flanks of the Hasper anticlinorium and Rathlin Lake synclinorium. Most suturing in the Hasper area appears to be primary rather than the result of deformation, but deformational suturing can occur anywhere as well. Both planar and dovetailed types can be most profitably viewed on the microscopic level.

(a) Planar Welded: Examples of cemented planar contacts (Figures 25a, 26) are common in lower Wynd strata, and are best sought where dips are gentle and bedding is regular. The example shown in Figure 25a is based on a thin section collected near Clairvaux Creek, from a road outcrop in which Cleavage A makes an angle of 25 degrees with southwesterly dipping bedding.  $S_{1A}$  and  $S_{2A}$  are both present in the slate below the contact, and both show a slight (less than 5 degree) tendency to deviate from a mean plane in the upper one-eighth of a millimetre.  $S_{1A}$  planes diverge and converge toward the bedding contact, at which they stop.  $S_{2A}$  planes, which show a shredded appearance at their upper ends, usually pass into the overlying fine-grained conglomerate without pause, and continue into it for about one-eighth of a millimetre. Beyond this



point these planes are deflected through 50-70 degrees so that in the conglomerate they become sub-normal to  $S_0$ . Small crenulation folds in trace  $S_0$  between  $S_{2A}$  planes suggest that domains on the up-limb side of  $S_{2A}$  have shifted upward by as much as 0.25 mm. Translation or microbending of  $S_0$  has produced left-lateral skewed, upright, asymmetrical microfolds (looking north-northwest); that is, the sense of rotation is the same in all domains. Bonorino (1960, p. 313) suggested that at the time of formation of such microfolds the compressive force was oblique to the S-surface which is now folded (compare also McBirney and Best, 1961).  $S_{2A}$  which lies tangent to the steeper northeast limbs of the microfolds and presumably parallel to the axial surface of the major fold, contains micaceous minerals which show signs of stretching and crumpling. Though micas still in  $S_0$  are scarce, those which are present have been bent to conform with the folded surface; micas parallel to  $S_{1A}$  remain comparatively straight and thick.

These microfolds show several important differences from those discussed under Cleavage A earlier: 1) microfolds in the earlier sample were in  $S_A$  rather than in  $S_0$ ; 2)  $S_2$  cut the attenuated steep limb and was discontinuous while in this example the steep limb shows little or no attenuation; 3)  $S_F$  in the earlier example cut both  $S_0$  and  $S_{1A}$  but in this example  $S_{2A}$  is essentially parallel to  $S_{1A}$ ; 4) sense of slip in the shear folded domains



described earlier was clockwise while here it is counterclockwise, though in both cases bedding has the same relation to Cleavage A in terms of attitude and sense; 5) displacements on  $S_F$  died out in both directions and were of a magnitude considerably less than that of the attenuated limbs of microfolds while here displacement is continuous and several times the magnitude of the fold amplitude; 6) in both cases  $S_{1A}$  is the oldest of the two cleavages present.

Cleavage B surfaces in this example appear to be equivalent to the  $S_{2A}$  shears.  $S_B$  consists of en echelon arrays of curved planes. Individual members of an array are usually less than 0.25 mm long, S-shaped, and paralleled by both fresh and stretched micas. Grain size is bi-modal and separated by several grade sizes; there is less than 25 per cent matrix, less than normal for Wynd conglomerates.

If an  $S_{2A}$  plane is traced through the boundary zone between lithologies it becomes curvilinear in the conglomerate, apparently as the result of repeated refraction away from large grains blocking its path. The general trend is toward the bedding normal but the path is made up of increments punctuated by deflection points (Figure 26). Individual deflections vary somewhat in trend but the overall trend proceeds a distance XY such that Y does not lie beyond the bedding normal with respect to X. From Y the trend deflects away from the bedding normal along a path YZ which has the same character as XY but



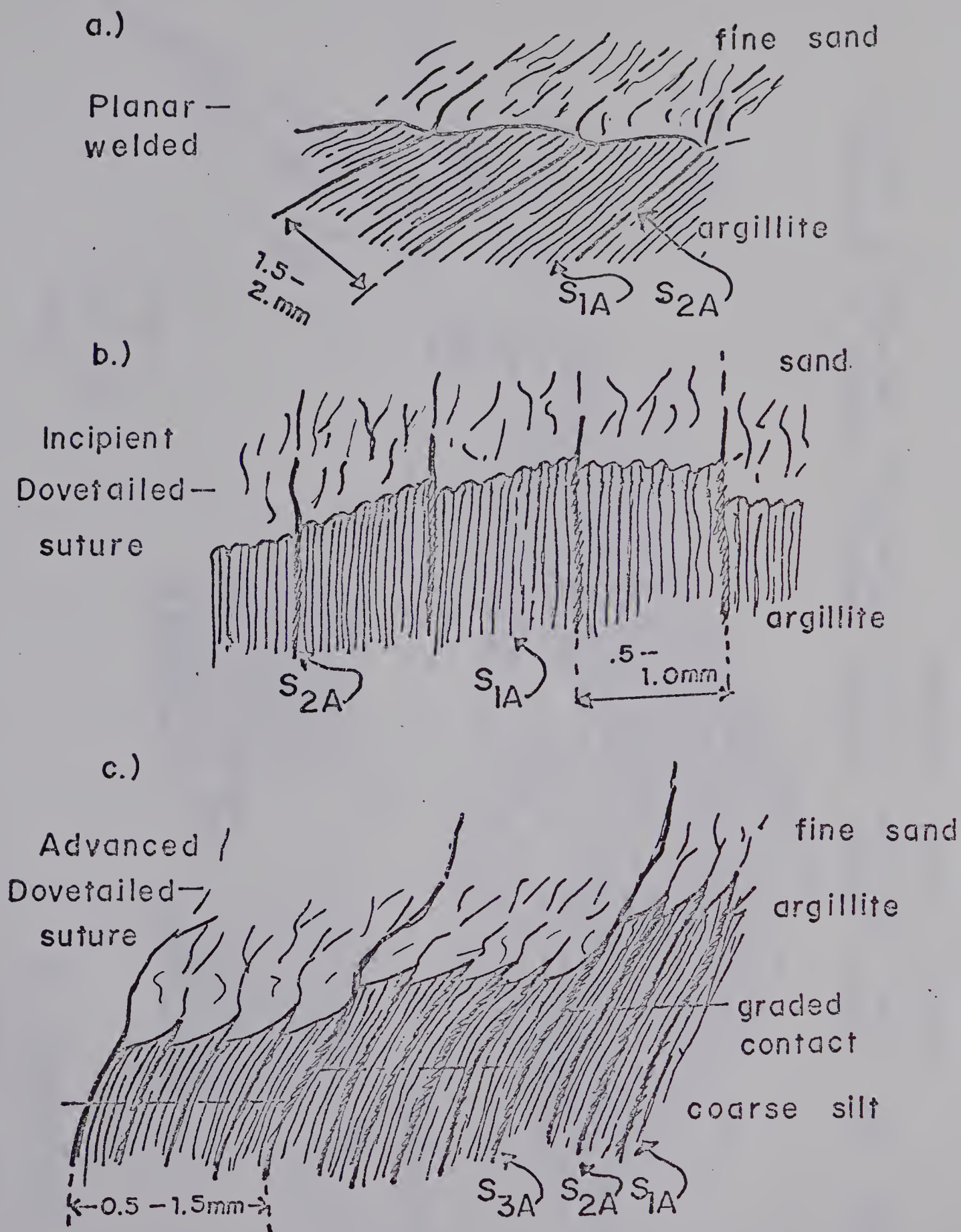
curves gently toward bedding. At some point along YZ there is a strong bifurcation in the trend path, one arm steepening while the other continues for a short distance before dying out. If the path of the steep arm is followed, then somewhere along it there is another bifurcation such that one arm repeats the performance of XY while the other usually dies out in an upward direction. However, beyond a boundary zone of 1 - 1.5 mm wide all planes become insensibly merged in an anastomosing pattern of curved planes; the pattern is contributed to by bifurcations from cleavage planes on either side.

The mean  $S_A$  plane is the acute bisectrix of the  $S_0$ - $S_B$  angle. The partially coincident paths of  $S_{2A}$  and  $S_B$  suggest that since the former records slip and post-dates  $S_{1A}$  then  $S_B$  is the result of direct componental shear formed late in fold development.

There are variations on this theme as well: one where argillaceous laminae a fraction of a millimetre thick are interbedded with a coarse conglomerate; a second where silt or fine sand is interbedded with slate. In the first case there are small diapirs of argillaceous material which contains a crenulated  $S_{1A}$  in which the axial surfaces of a crenulation make an angle of about 30 degrees with bedding; the conglomerate is either uncleaved or too coarsely cleaved to be discernible in thin section; since there is no sign of shearing the example may be intermediate between the case above and that described under Cleavage A.



FIGURE 25: Welded contacts





Entering Zone of  
Sigmoidal Domains  
& Anastomose  $S_B$

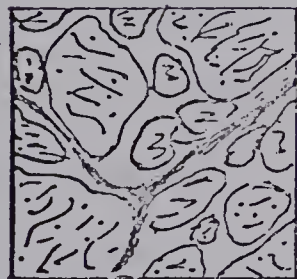


Zone  
of  $S_B$

Traceability



[ 0.5-  
0.6mm ]



Mean  
Bedding-

Normal

Mean  $S_B$  (Local Bedding L)  
Mean  $S_A$

0.5 mm.

Congl.

Mean

$S_0$

$S_0$

$S_{1A}$

$S_{2A}$

Slate

Planar welded contact showing passage of spectral  
type Cleavage A into bifurcating Cleavage B across  
gently arched bedding.

FIGURE 26



The second example is again one in which there are two  $S_A$  planes, the wider spaced set cutting through both the slate and the silt; the  $S_{2A}$  planes are deflected around silt grains in the lamination to produce a 'knotted pine' effect reminiscent of that in poorly sorted slates; if the lamination was thicker a good Cleavage B would be produced.

b) Dovetail Sutured Contacts: Good examples of primary intrusion of argillaceous material into sandstone and of loadcasting can be found in outcrops of lower Wynd strata on the southwest limb of the Meadow Creek anticlinorium near Clairvaux Creek and elsewhere; cleavage is usually present in these examples. Since sutured contacts have not suffered inter-stratal slip but may be associated with lithological changes, such as graded bedding, and structural effects, a host of relationships can best be studied by examining them.

A useful example was collected from lower Wynd strata on the southwest limb of the Miette River anticline (Figure 37, Unit A). Argillaceous material here has partially penetrated the basal part of a 1 foot thick, coarsely cleaved conglomerate along an irregularly sutured contact. Higher up in the conglomerate are several vertically elongated, irregularly shaped argillite 'blobs' (Figure 27). Mesoscopically, Cleavage A in the underlying slate dips 74 degrees southwest in bedding which is very



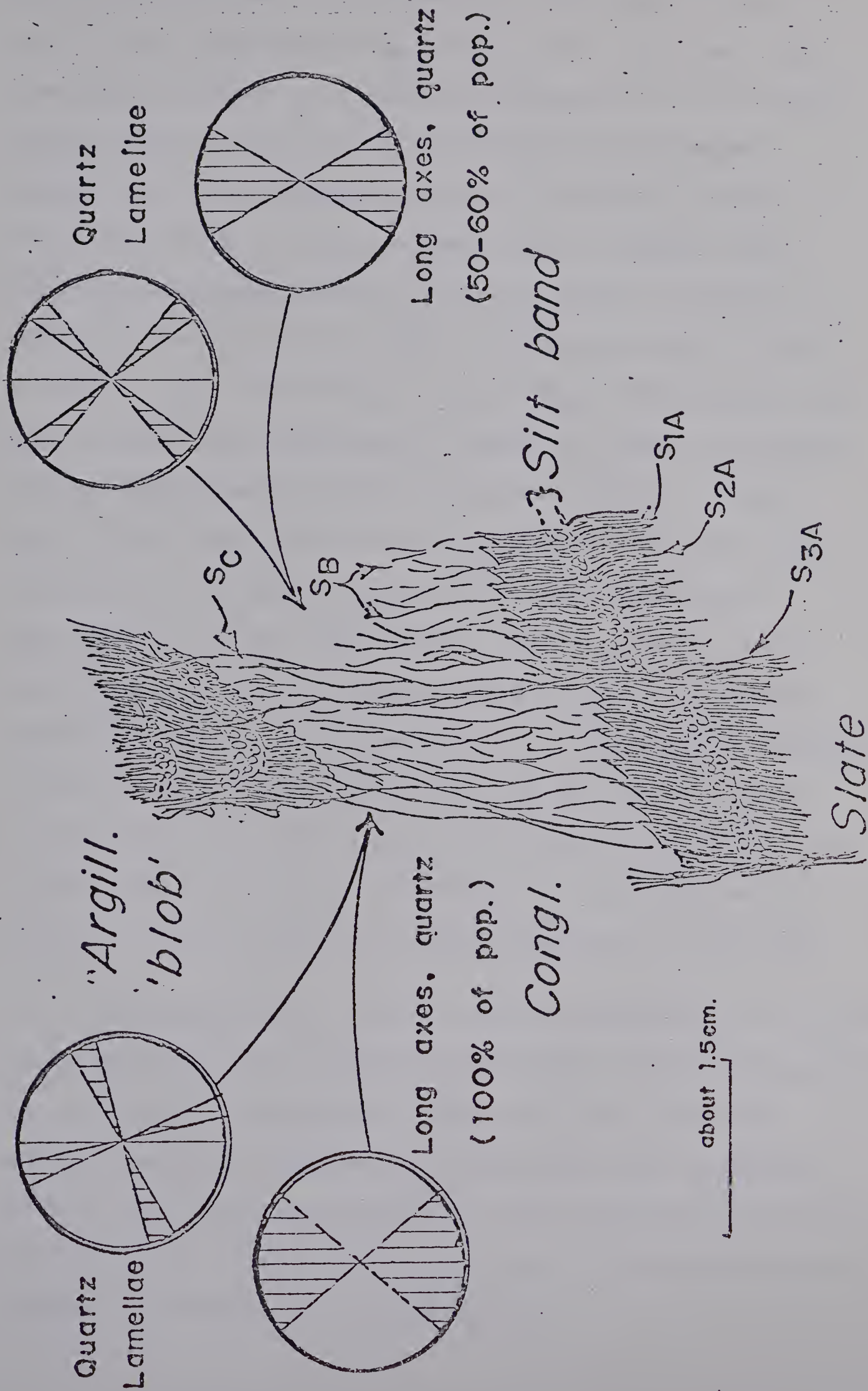


FIGURE 27  
Spectral, interrupted and refracted Cleavage A  
along a micro-sutured bedding contact. Cleavage  
and internal fabric of overlying conglomerate reflect  
disruptions along the contact.



thin, irregular and discontinuous. The slate is cut at 0.5-2 mm intervals by  $S_{2A}$  along which there has been translation; there is a further splitting up of the slate by  $S_{3A}$  which occurs at 1.5-2 cm intervals and shows normal fault type displacements on the order of about 5 mm (Figure 25c). These normal faults together with irregular movements along  $S_{2A}$  have worked to cause an apparent reduction in the dip of bedding as seen in thin section.  $S_{3A}$  cuts bedding,  $S_{1A}$  and  $S_{2A}$ ; both  $S_{3A}$  and  $S_{2A}$  pass up into the conglomerate though  $S_{1A}$  planes terminate against conglomerate grains along the contact. Along  $S_{3A}$ , on the down-thrown side,  $S_{1A}$  planes converge on  $S_{3A}$  by from 5 to 10 degrees while on the up-thrown side they diverge by the same amount. Both  $S_{2A}$  and  $S_{3A}$  are deflected toward the bedding normal by about 30 degrees within the first few millimetres after crossing the bedding contact, but a similar deflection in the opposite sense occurs shortly so that essentially there is no difference between the orientation of cleavage in the conglomerate and  $S_{3A}$ . Both are an axial plane cleavage in this case.

The microscopic fold in the overlying argillite 'blob' is asymmetrical and inequant, both limbs terminating against the jacketing conglomerate. The left limb terminates abruptly against conglomerate but a few of the boundary pebbles have been incorporated in the argillaceous material. In the crestal region of the fold the argillaceous material assumes the shape of an asymmetrical



J-shaped arc. The upper part of the 'blob' is penetrated by an extremely close spaced Cleavage A (0.05 - 0.08 mm spacing), which deviates around any coarse silt grains which are present. When these  $S_{1A}$  planes reach the silt band which passes through the 'blob' they separate into a network of fine planes. Fragments of platy minerals and chips of feldspar present in the silt band lie sub-parallel to the nearest cleavage plane. At intervals of 0.67-1 mm there is an  $S_{2A}$  cleavage which marks zones of close-spaced  $S_{1A}$  planes separated by highly strained domains; there has been shearing along these  $S_{2A}$  zones so that a downward movement of the axial region relative to the right lib has taken place. Individual displacements are irregular, however.

Argillaceous material below the silt band appears to have been appressed so that cleavage planes now lie extremely close together, especially along the lower margin of the 'blob'. Cleavage planes originate at the lower boundary of the silt band by simple bifurcation or splaying of the cleavage planes which pass through it, but the new planes soon become parallel to each other and to the axial surface of the small fold. They continue parallel until the last 0.5 mm before the lower boundary of the 'blob' is reached, at which point they again show alternate convergence and divergence. Offset domains between  $S_{2A}$  are also present below the silt band, again suggesting that the axial region of the micro-fold moved



down and the flanks up. No coarse silt grains are visible at low power.

Conspicuous everywhere along the lower boundary between the conglomerate and the 'blob' are offsets along  $S_{2A}$  such that the finer lithology is tightly sutured to the conglomerate in a mortise-and-tenon structure. Large competent grains cause deflections of cleavage planes except in the axial region where  $S_{2A}$  surfaces are undulose but essentially continue on parallel trends to the edge of the thin-section. In handspecimen these pass into the basal slate where they once more become  $S_{2A}$ .

In the first millimetre of conglomerate below the right flank of the micro-fold most small elongated quartz grains and rock fragments lie sub-parallel to the  $S_A$  cleavages; in the axial region mica and dolomite, elongated quartz, and rectangular rock fragments up to 0.5 mm long lie parallel to  $S_{2A}$ . In the conglomerate iron staining and mica flakes mark the cleavage planes.

In angular terms:  $S_{1A}$  and  $S_{2A}$  on the right side of the microfold converge on a mean axial surface by 5 - 8 degrees, but as they pass into the arenite they are deflected by an average of 23 degrees so that in the conglomerate below the right flank they trend 15 degrees toward the true bedding normal. In the axial region cleavage in the conglomerate defines a mean plane which



parallels the axial surface but varies between  $S_{2A}$  and  $S_{3A}$  and therefore approximates the axial surface of the Miette River fold. The axial portion of the micro-fold overlies a downwarp of a down-thrown  $S_{3A}$  domain in the underlying slate.

Deformation lamellae and kink bands are abundant in the quartz grains of the conglomerate. Most kink bands lie at 90 degrees to the lamellae and parallel the long axes of quartz grains. The trends of 80 lamellae populations were measured around the micro-fold and two maxima were found to occur at 90 degrees to each other; the trends of these lamellae are shown in Figure 27. In the crestal area one maximum lies between 13 and 25 degrees counterclockwise from the mean axial surface; the other lies 60 to 72 degrees clockwise from the mean axial-surface, indicated by the N-S line of the figure. In domains below the flank all lamellae trend 35 to 50 degrees off a mean axial surface, with both clockwise and counterclockwise trends being equally well represented. Bonorino (1960) has suggested that since the planes of maximum shear strain remain fixed during plastic deformation by non-rotational strain, then so should grains whose glide planes become trapped in such shear planes; no increase in deformation, he says, could change this. The argument suggests a mechanical basis for a similar line of reasoning by Christie et al (see earlier discussion). Yet, here we have 2 subdomains a matter of millimetres



apart where there has certainly been movement. It is true, however, that one set of lamellae lies at a very low angle to the present attitude of bedding, and earlier examples have strongly suggested that in the cleaved folds of the Jasper area bedding may have closely followed one of the planes of high shear during late stages of folding. Therefore, it is likely that lamellae bearing grains have been disturbed by the shearing effects along  $S_{3A}$ .

To test this hypothesis the long axes of strongly inequant quartz grains around the micro-fold were also measured in an effort to determine whether there was any correlation between their preferred orientation and cleavage. In the axial region, most elongated grains lie at 10 to 15 degrees to the mean axial surface, but the total range is 6 to 42 degrees (Figure 27). Away from the axial region the mean inclination of elongated grains is between 20 and 30 degrees to the axial surface, but up to 50 per cent of the grains measured in some domains had some other orientation. Some of these grains are broken or sheared normal to their long axis, the shear planes roughly paralleling local cleavage (cf. Bonorino, 1960; Billing, 1956); some of the broken grains display irregularly shaped albitized patches along the discontinuity and mica flakes have sometimes been bent by the shearing past of the two pieces of the broken grain. Thus, there also seems to be a fairly strong correlation between the long axes of quartz grains and cleavage.



## Kindred Structures

Several structures which appear to be related to both folding and cleavage deserve a brief discussion. These include: cleavage mullions, kink folding and parasitic folds, fissuring in sandstones and 'intersecting oblique shears'.

### 1) Cleavage Mullions

Charlesworth et al (1967) and Charlesworth and Evans (1962) have discussed these structures from thin Old Fort Point siltstones interbedded with slates on the overturned northeast limbs of anticlines. They report that individual blocks have been rotated 12 degrees toward Cleavage A (Figure 7), so that at present the long axes of the mullions parallel Cleavage A. As noted earlier, the sense and magnitude of this rotation is comparable to that of the blocks shown in Figure 8.

### Tentative Working Hypothesis

These structures resemble the sort of structures seen in the axial regions of folds in which Cleavage E is well developed in Old Fort Point limestones and slates (Figure 42). An analysis of the strain involved in the development of the mullions (Charlesworth and Evans, 1962) suggests that some shearing occurred parallel to Cleavage A.

### 2) Kink Folds and Parasitic Folds

Mesoscopic kink folds and parasitic folds are best developed in Old Fort Point beds along the Meadow Creek



Anticlinorium.

a) Kink Folds Kink folds occur in slates of the Old Fort Point Formation in which Cleavage A is highly penetrative (Figure 28a, b). They have been discussed by Charlesworth et al (1967) and described at length by Weiner (1966).

Kinking involves Cleavage A surfaces only. Each kink fold is monoclinial and ranges in length from less than 3 to more than 100 mm. In all cases  $S_A$  has been rotated  $10 - 40^\circ$  counterclockwise (looking northwest) from a mean Cleavage A plane. At each end of the monocline is an axial surface which separates the kinked zone from the 6 mm to 150 cm wide undisturbed zones on each side. The paired axial surfaces, which vary in strike from  $N 30^\circ W$  to  $N 90^\circ W$  and dip consistently northeast at about  $40^\circ$ , are roughly normal to Cleavage A. Kink zones are traceable along strike for up to 50 feet, and occasionally cross one another.

Such kink folds, together with graded bedding, jointing, block mullions and mesoscopically bent Cleavage A can also be observed in sections exposed along the new Yellowhead Highway where it passes through the Minaga Creek synclinorium. The strata involved belong to the lower Wynd Formation (Figure 28b).

Microscopic kink folds have also been observed, mostly in thin sections cut from Old Fort Point slates. Relations are much the same as those seen mesoscopically: axial surfaces lying at  $80-85^\circ$  to Cleavage A; an intervening



monocline making an angle of  $20-40^{\circ}$  with undisturbed  $S_A$ ; a counterclockwise sense of rotation; and a general lack of ruptured axial regions.  $S_A$  cleavage is marked by thick chlorite books and plates which may be sharply flexed or occasionally broken near the axis of bending. In some sub-domains  $S_A$  zones appear to be about 25-40% thicker near the axis of bending as compared to  $S_A$  zones which have not been disturbed.

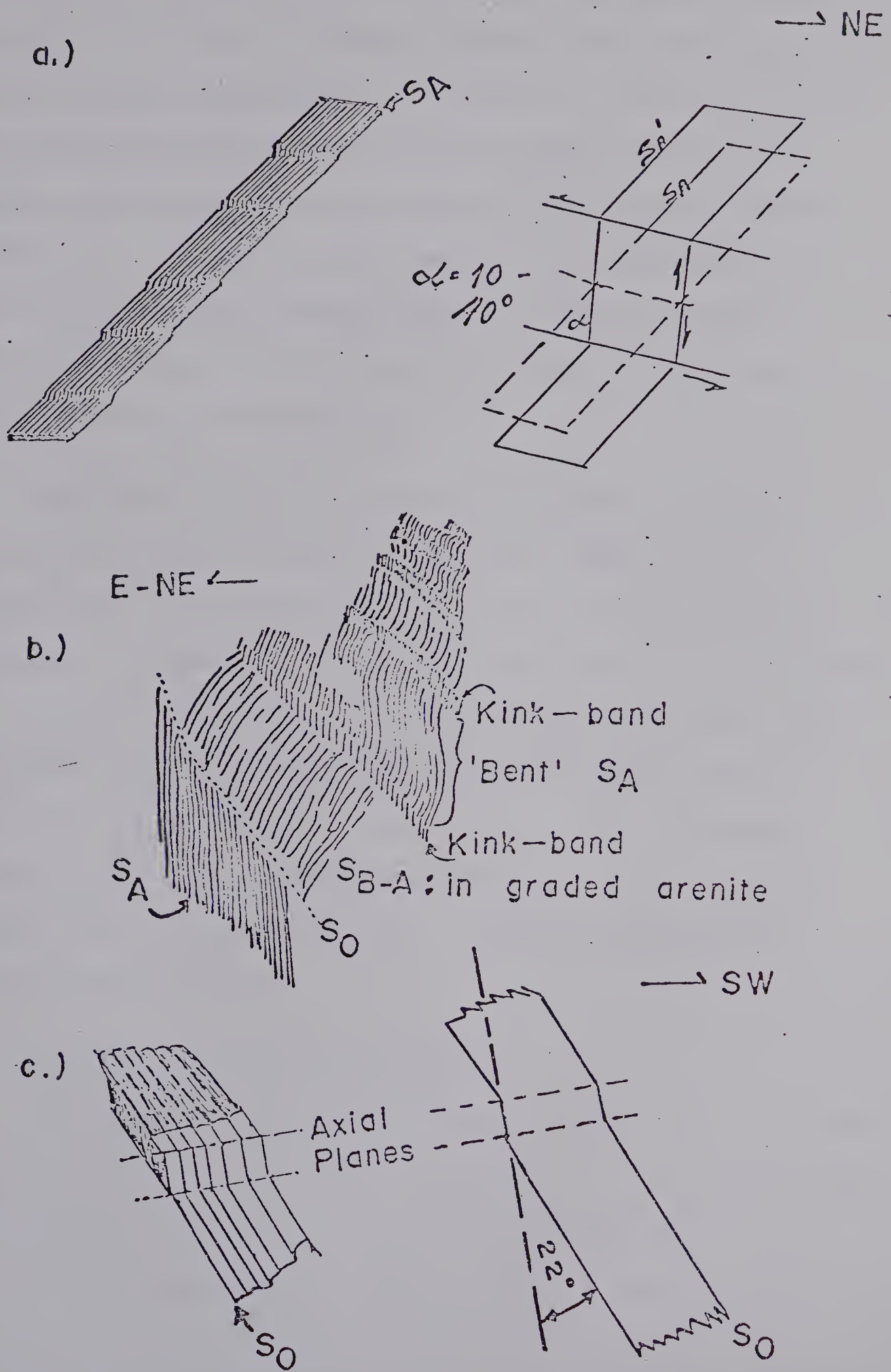
#### Tentative Working Hypothesis

Weiner has postulated laminar gliding along Cleavage A plus internal rotation of  $S_A$  as the principal operating mechanism. He suggested that the axial surfaces of the kink folds are strain discontinuities which define the limits of deformational gliding. No slickensides have been observed along the axial surfaces, even though some of these are fracture zones both in thin section and in outcrop. Thus it is unlikely that the kink folds developed by shearing along their present axial surfaces.

b) Parasitic Folds Parasitic folds similar to the kink folds described above occur in thinly bedded limestones of the Old Fort Point Formation along the new highway across the axial zone of the Meadow Creek Anticlinorium. In one outcrop (Figure 28c), several thin finely crystalline limestone beds, averaging about 1 cm in thickness, have been kink folded over a stratigraphic zone several feet thick. These monoclinal kinks can be followed for more



FIGURE 28: Typical relations of mesoscopic kink-folds





than 30 feet along strike. Width of the zone is in the range of 2 or 3 cms to several inches, while amplitude is usually several centimetres. Bedding in the single limb has been deflected 25 to 30 degrees away from the mean bedding plane in a counterclockwise sense (again looking northwest). Since bedding inclines  $55^{\circ}$  southwest the acute angle between bedding and the northeast dipping axial surfaces of the kink folds is about 60 degrees. There is no sign of rupturing.

Disharmonic parasitic folds also occur in highly chloritized slates along the southwest limbs of the Meadow Creek anticlinorium. A series of thin-sections cut normal to the axis of one of these showed that Cleavage A is finely crenulated and cut at varying intervals by an incipient normal faulting which resembles the cross-foliation discussed under Cleavage A. This structure differs, however, in that here Cleavage A may be either sharply bent, sheared abruptly, or merely attenuated in the presence of it.

#### Tentative Working Hypothesis

The observed micro-faults lie from  $50$  to  $80^{\circ}$  clockwise (looking northwest) of normal Cleavage A. In one instance an extremely narrow (0.03 mm) kink fold was found cut by one of these micro-faults; the dip of the axial surfaces of the kink fold is normal, while the micro-fault lies  $60^{\circ}$  clockwise of them. All of the observed micro-faults occurred at infrequent and irregular intervals, their local



attitude varying according to the attitude of folded Cleavage A. It is likely that these structures differ from both kink folds and the interrupted Cleavage A discussed earlier because: Cleavage A has been buckled, crumpled, stretched and sheared parallel to the length of its own domains rather than transversely; and external rotation (buckling) is more prominent than internal rotation, the micro-faulting apparently being localized by the external rotation.

## 2) Fissured Sandstones

Strong cleavage development in folded sandstones may cause open fissures to develop along certain zones in weathered outcrops. In the Jasper area, the fissuring effect is commonly seen in lower Wynd conglomerates (Figure 29b). It is also present in the axial zone of the Miette River fold (Figure 36).

### Tentative Working Hypothesis

Hill (1963, p. 291ff) suggests that fissuring 'represents excessive shearing and flattening' of the folded rock along preferred zones 'in response to bending of the bed'. He believes it develops at a late stage of folding so that the final movements of folding act along the fissures and thereby increase the dip of the fold limbs. Displacements of this type are on the order of an inch or two. Near fold hinges, fissures will lie between the two theoretical high shear stress planes, whereas on the limbs fissures will generally occur nearly normal to bedding. Fissuring seems to develop better in sandstones



which are comparatively thicker than surrounding beds, suggesting that it develops best in beds which acted competently throughout the folding.

#### 4) Intersecting Oblique-Shears

Weiner (1966) has described zones of intense folding and shearing from several outcrops which lie stratigraphically near the contact between the Old Fort Point and Wynd Formations (Figure 29a). These outcrops, from the central zone of the Meadow Creek anticlinorium, are not believed by him to be typical since these effects are lacking elsewhere.

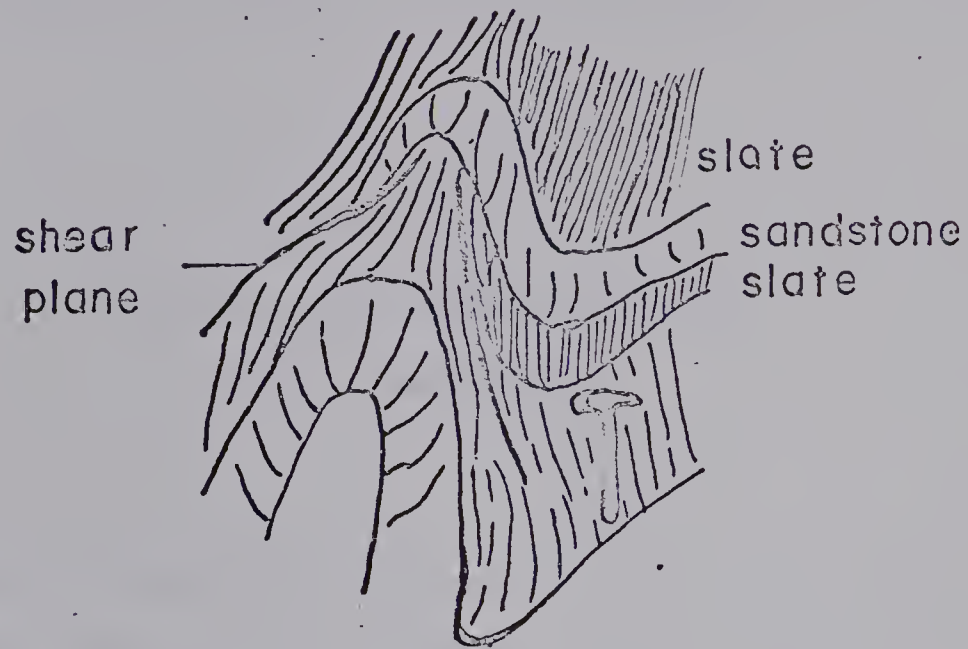
#### Tentative Working Hypothesis

The structures described by Weiner were thought to represent local 'decollement'. However, these features resemble what de Sitter (1956, p. 227) has termed oblique-shears. So far as the present study is concerned, the structures described by Weiner, de Sitter's oblique shears, and the numerous bedding faults in the Jasper area (Figures 16, 30, 36) can be treated together as oblique-shears. Weiner's suggestion that the structures described by him indicate differences in overall competency between the stratigraphic units involved and slight differences in style of deformation in the different units is the sort of general pronouncement that can be applied to all of these structures. In all cases cleavage in the beds involved has been bent and otherwise disrupted, bedding

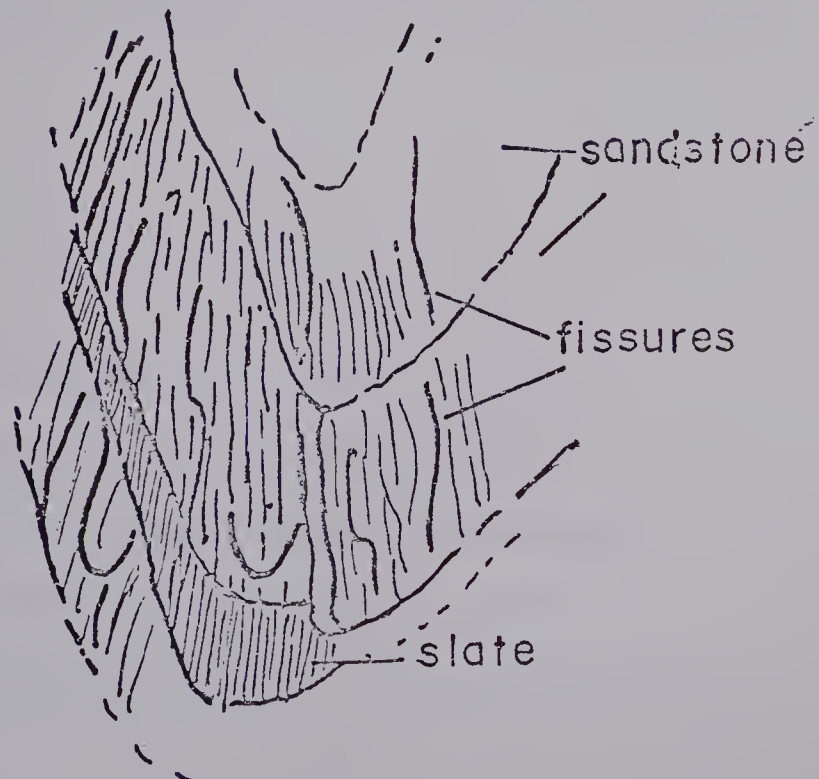


FIGURE 29: Fissuring in sandstones, and intersecting oblique shears

a.)



b.)





is usually cut at a low angle somewhere along the structures, and there is always evidence of translation of the material on opposite sides of the structures.

### Geometry and Fabric Analysis of a Simple Fold

A detailed study was carried out on a single fold in lower Wynd strata along the east bank of the Miette River about one-half mile east of Geikie Station and due north of the confluence of Meadow Creek with the Miette River (Figure 5). All orientation data were processed using an IBM-360 computer and updated existing Fortran IV programs.

#### Structures Present

In the railroad cut, the beds define a tight, upright anticline trending N 47°W, roughly parallel to the axes of the Meadow Creek and Minaga Creek macrostructures. The fold limbs dip at 55-60°, and the axial surface is essentially vertical (Figures 30,31).

#### Lithological Contacts

The interbedded arenaceous and argillaceous units



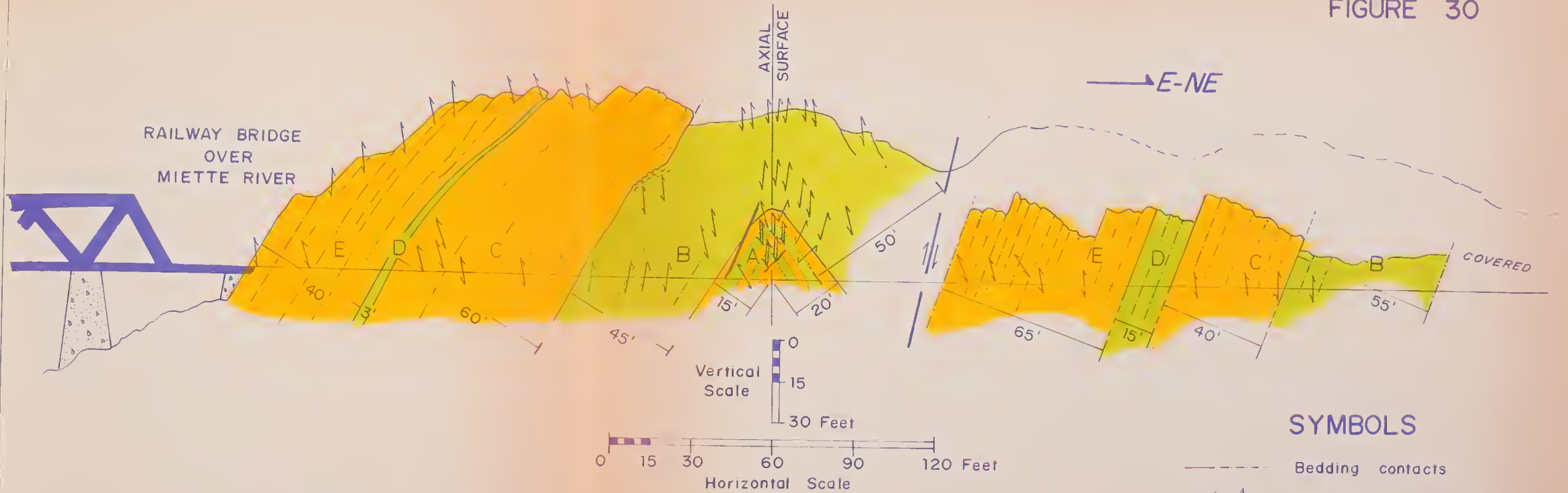
studied have a combined thickness of about 160 feet (Figure 30). Individual units range up to 60 feet in thickness, but most of them probably pinch out along strike.

All three types of bedding contact are present. Bedding planes are found to be planar on scales of 50ft<sup>2</sup> or less in arenites, and on a slightly larger scale in slates; bedding-plane roughness appears to vary with position on the limbs but in both cases strike readings are fairly constant regardless of structural position (Figure 31). Inter-unit contacts are therefore reasonably sharp and, where changes in grain size are also sharp, as between fine-grained conglomerate and slates or siltstones, they can be considered planar as well. However, both lateral and upward gradations in texture can occur over intervals of several feet, especially where the grade sizes in adjoining beds are more uniform; both continuous and discontinuous graded bedding occurs. Sedimentary structures in coarse grained arenaceous units include cross-bedding and cross-lamination, scour channels and channel residues, and load-casts from several centimeters to several feet across. Argillaceous units generally show well developed bedding lamination, but graded textures are common both in the laminated slates themselves and in the interbedded silty slates. Bedding plane slickensides are prominent on the upper surfaces of arenites in Unit A and at the top of slate Unit B.



# CROSS-SECTION OF MIETTE RIVER FOLD

FIGURE 30



## WYND FORMATION

- Argillite and siltstone
- Sandstone and conglomerate

A, B etc. Local stratigraphic divisions, thicknesses as shown

## SYMBOLS

- Bedding contacts
- Cleavage, axial-plane cross-foliation, attitude as shown.
- Kink-folds
- Tension fractures
- Bedding fault
- Inferred tectonic fault



## Cleavage

Cleavage was measured both along the railroad cut and on a traverse across the southwest limb and crest of the anticline (Figures 30, 34a,b).

## Mesosopic Relations

Cleavage A is penetrative in all slates, and it is essentially an axial plane cleavage. The equal area projection (Figure 34b) indicates that Cleavage A dips steeply southwest and that the distribution is asymmetrical; however, the asymmetry is simply due to lack of measurements on the northeast limb where intensive weathering and recent slumping have altered and obscured relationships. Figure 35a shows that as the limbs steepen beyond  $40-50^{\circ}$ , the dip of Cleavage A begins to decrease, though both bedding and cleavage dip in the same directions. The overall rate of decrease for the southwest limb ( $2^{\circ}/10^{\circ}$ ) is slightly greater than for the northeast limb ( $1^{\circ}/10^{\circ}$ ).

Cleavage in the arenaceous units forms a tight fan about the axial surface. A plot of the acute angle between bedding and cleavage (Figure 35a) shows that there are two cleavages present, as mentioned in the earlier discussions of graded and sutured contacts. Except in the axial region in the core of the fold, where cleavage has been emphasized by fissuring, it is impossible to differentiate them in the field. Furthermore, because the different lithological units show grading from place to place, Cleavages A, B and



C tend to merge insensibly with one another. To test the hypothesis that grain size may have some control on the orientation or type of cleavage which will develop in competent units, two sections were chosen from the thick sandstone near the core of the fold. Both span essentially the same structural and stratigraphic zones. The first has already been discussed under interrupted graded bedding; orientation data are shown on the equal area projection, Figure 37a. Figure 37b shows the orientation of cleavage in the comparison zone, a 9.5 foot thinly bedded sequence on the northeast limb. Both homogeneous and heterogeneous units were present in this interval so data was recorded according to the size of the coarsest material present along the zone of measurement, a one foot wide traverse normal to bedding. Despite the discrepancy in sample size, correlation between the two limbs was good. Accordingly, the orientation data for the interbedded sequence was plotted against grain size (Figure 38). The completed diagram predicts what the orientation of cleavage would be for various grade sizes; but the percentages of each modal size present in the sampled zone, its lower size limits, and the number of modes present have been ignored; the result is thus only a poor first approximation. An investigation which takes into account these additional factors might well help to establish a proper probability zone which could then be tested elsewhere in the Jasper area and in other parts of the world.



## Microscopic Relations

Spectral type Cleavage A is present in the slates, both  $S_{1A}$  and  $S_{2A}$  being present. Inter- $S_{1A}$  domains and inter- $S_{2A}$  domains belong to Branch 1 of the Spectral Group, with most of the offsetting of bedding taking place along opposite sides of  $S_{2A}$  planes. On the limbs of the fold,  $S_{2A}$  planes at lithological contacts mark well developed microsutures along which the up-limb side of an  $S_{2A}$  domain has been translated upward with respect to the down-limb side; most  $S_{2A}$  planes pass into Cleavage B in adjacent arenites. In the axial region of the fold,  $S_{3A}$  is present (described under micro-suturing; Figure 27) and cuts both  $S_{2A}$  and  $S_{1A}$  planes at low angles. In the Miette River fold  $S_{3A}$  is an axial plane structure along which most of the translation in these cleaved beds seems to be concentrated.  $S_{3A}$  passes upward into arenites without any sharp deflection in trend, unlike the passage of  $S_{2A}$  into Cleavage B; in the Miette River fold  $S_{3A}$  is the acute bisectrix of the Cleavage A/Cleavage B intersection, whereas Cleavage A is generally the acute bisectrix of the Cleavage B/bedding intersection.

In thin section, Cleavage A and Cleavage B show convergence upon areas where the number of grain-to-grain contacts is high and the grains in contact are coarser than the matrix (i.e., where pebbles occur in sandstones or where silt or sand particles occur in inter- $S_A$  domains or as bedding laminations in slates). Flattened sigmoidal



domains are common between both  $S_B$  and  $S_C$  planes, but in the case of  $S_C$  en echelon arrangement is not as prominent as it is in inter- $S_B$  domains.

Fissuring along  $S_B$  and  $S_C$  zones is well developed in Unit A arenites in the heart of the fold.

### Parasitic Folds

Bedding lamination in the upper 3-6 inches of slate Unit B has been locally folded into smoothly arched, regularly spaced parasitic folds with amplitudes of about 4-5 cms and spacing of about 10-12 cms. Slate in these parasitic folds appears to have yielded primarily by longitudinal flexuring and sliding parallel to bedding lamination. Cleavage A planes of the underlying slate die out upwards in the Unit just where the first noticeable signs of flexuring and sliding appear.

### Joints

Both ac and h01 joints can be readily recognized (Figure 32) in the arenaceous beds; h01 joints appear to fan normally about the axial surface, though too few readings were taken to establish this with any great degree of certainty.

A few nearly vertical joints sub-parallel to mesoscopic Cleavage A were found near the top of slate



Unit B along the base of the outcrop; surfaces of these have a plumose pattern and feel 'scaly' when swept with the hand. The 'shaft' of these plumes defines a weak sub-horizontal lineation lying in the joint planes.

'Trails' of possible small feather joints, usually less than 2 cms wide and resembling small triangular pits, parallel slickensides on some bedding surfaces in Units A and B.

### Lineations

The best bedding plane slickensides occur at the top of slate Unit B, near the base of the outcrop. Pitch of these slickensides is  $90^{\circ}$  relative to the lineation marked by the sub-horizontal bedding/cleavage intersection. Bedding plane slickensides with the same trend are locally visible on the upper surfaces of arenite beds in Units A and E.

Slickensides and polished surfaces are also present on many ac joint faces in Unit E, both along the Miette River and east of the fold. On the southwest limb these slickensides plunge  $17^{\circ}$  to  $25^{\circ}$  southwest in joint planes which dip  $65 - 90^{\circ}$  southeast.

Slickensides and mineral streaking, the latter in the form of 'smeared' or 'drawn out' chlorite and muscovite books, are occasionally visible along freshly split



Cleavage A surfaces.

### Oblique Shears

Oblique shears, as defined above, are of two types: bedding plane or near bedding plane faults, and planes of apparent kinematic discontinuity oblique to bedding. Of the former, the bedding fault occurring near the core of the fold (Figure 36) has caused the most obvious disruption of earlier fabric. This fault originates near the base of the outcrop and just below the top of Unit A, appearing in bedding which dips about  $50^{\circ}$  southwest. Higher up in the southwest limb the fault 'skips' up-section to enclose an angle of 15-20 degrees with bedding that dips  $35-40^{\circ}$  southwest. The fault eventually dies out beyond the base of the strongly cleaved Unit B slates.

Several small near bedding faults also appear in the strongly flexed beds in the very core of the structure.

Another fault, this time along the bedding contact between Units B and C, occurs in the vicinity of the parasitic folds described above (Figure 33). This basal detachment plane also steepens until it makes an angle of 25-30 degrees with bedding. The fault 'splays' as it steepens and begins to die out in Unit C arenites.



FIGURE 31 Bedding orientation — Miette River fold

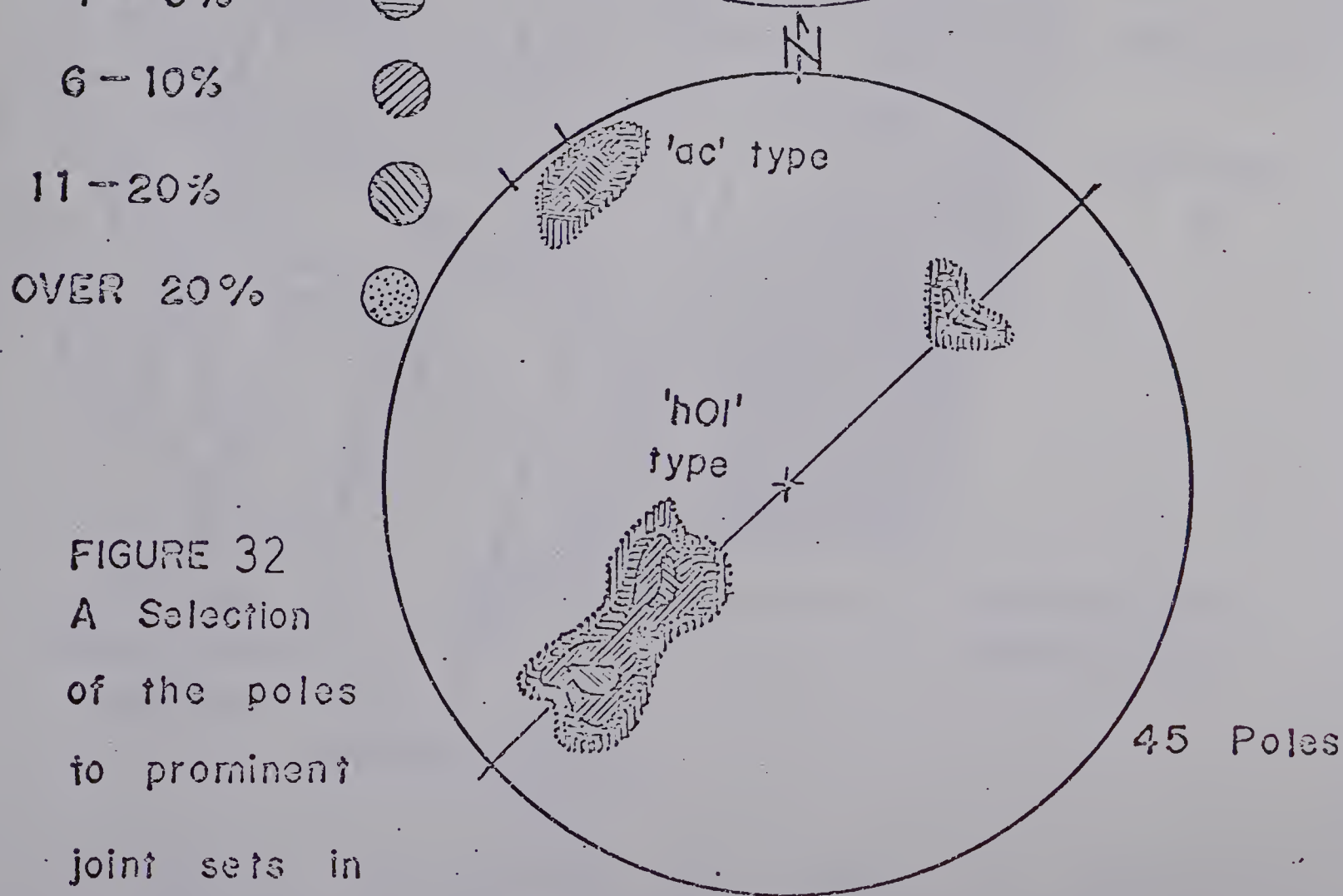
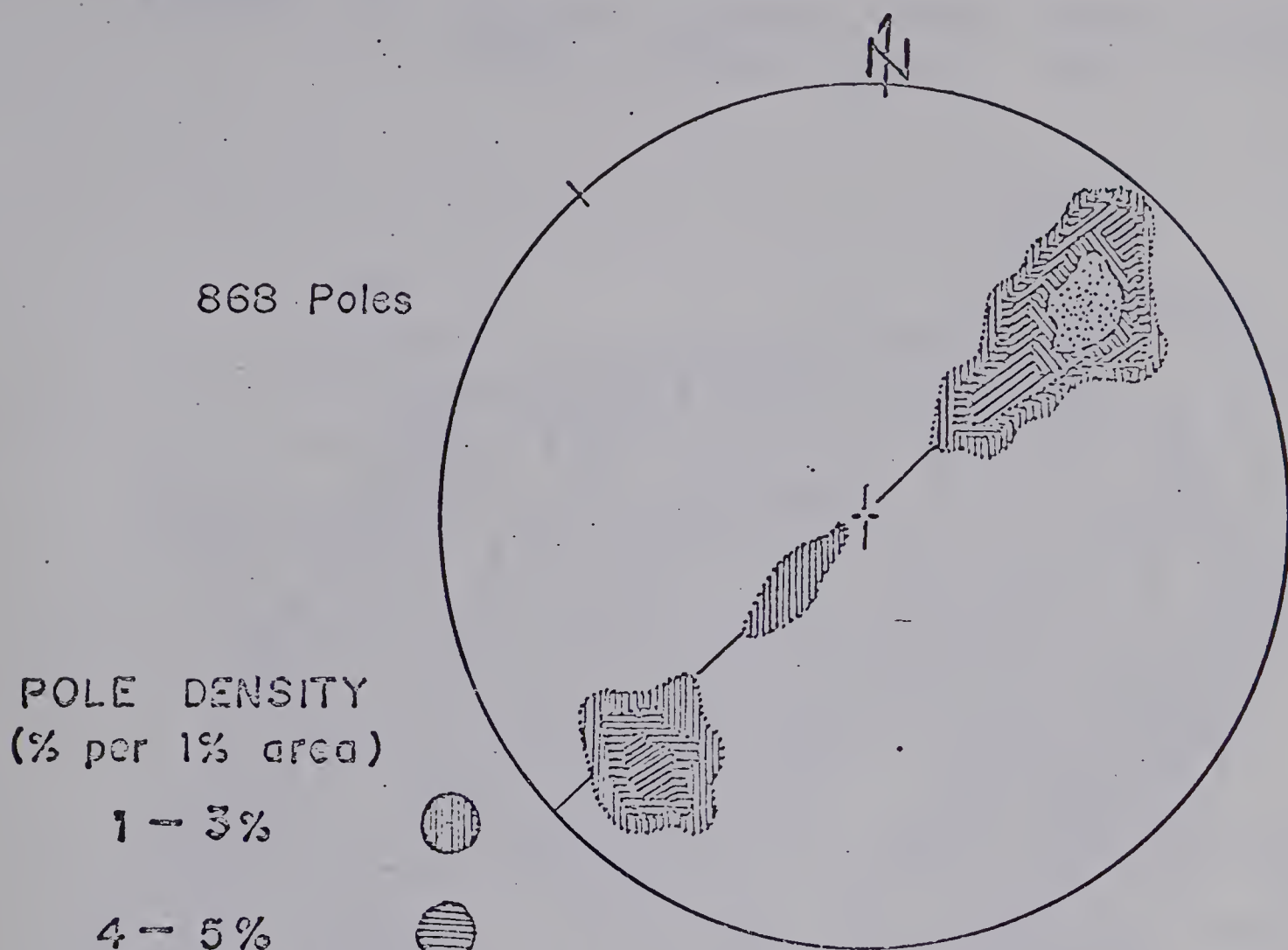


FIGURE 32

A Selection

of the poles

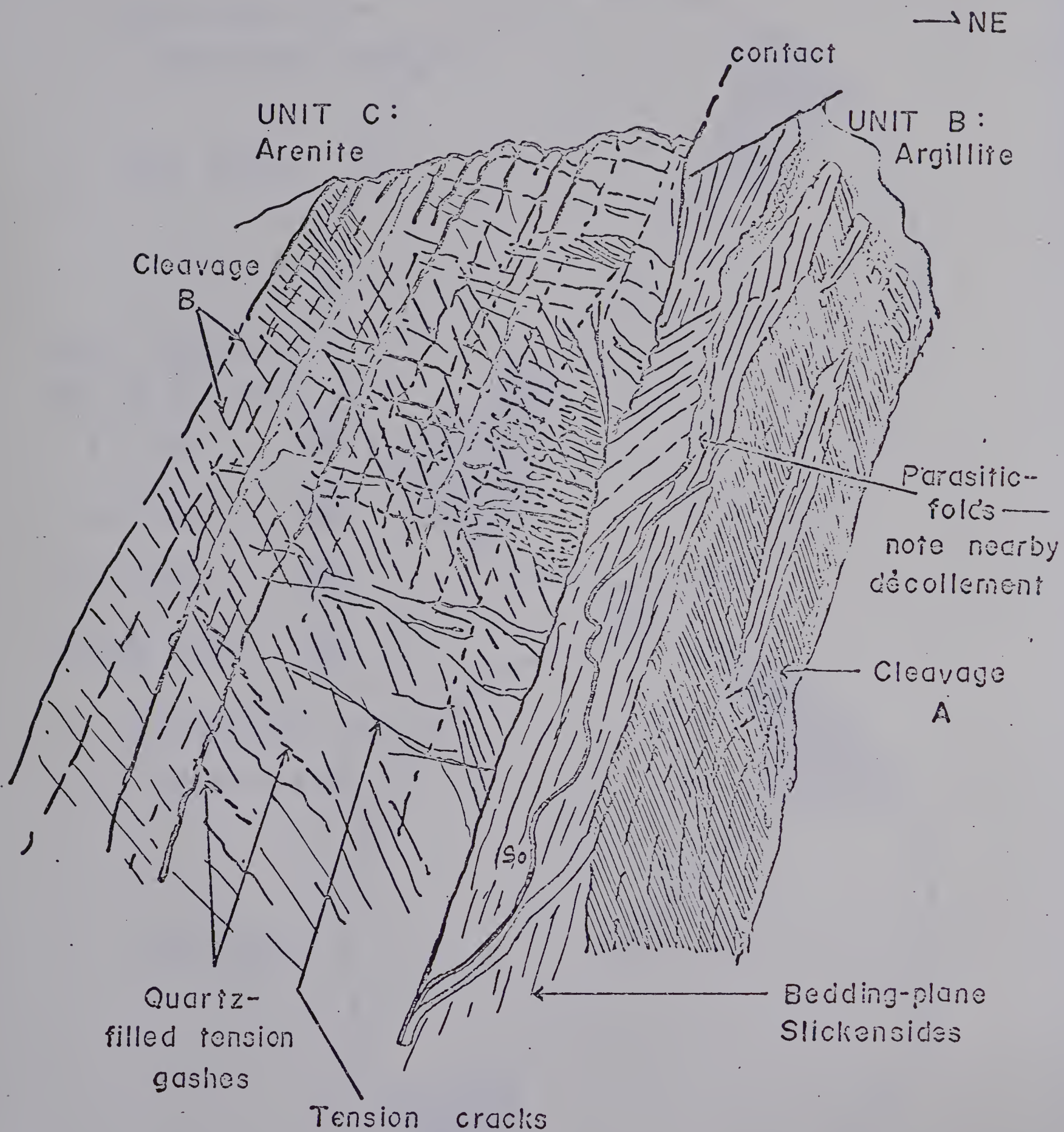
to prominent

joint sets in

arenites of the Miette River fold.



FIGURE 33 Cleavage, tension cracks and parasitic—  
folds — Miette River fold



This is a perspective view—hence the exaggerated variation in bedding thickness; about 50 feet of beds shown.



FIGURE 34 Cleavages A and B, Miette River fold.

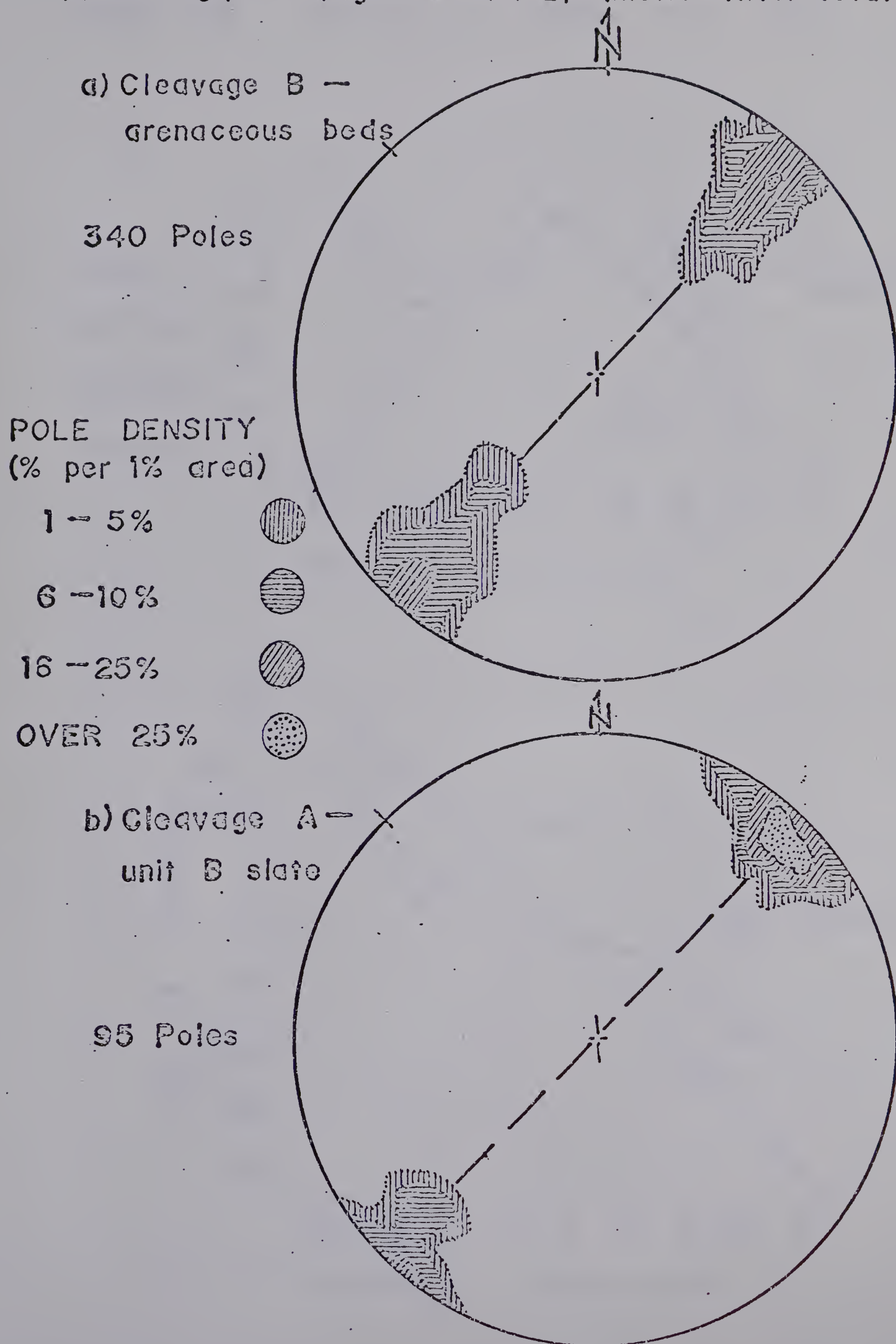




FIGURE 35 Cleavage in Miette River fold.

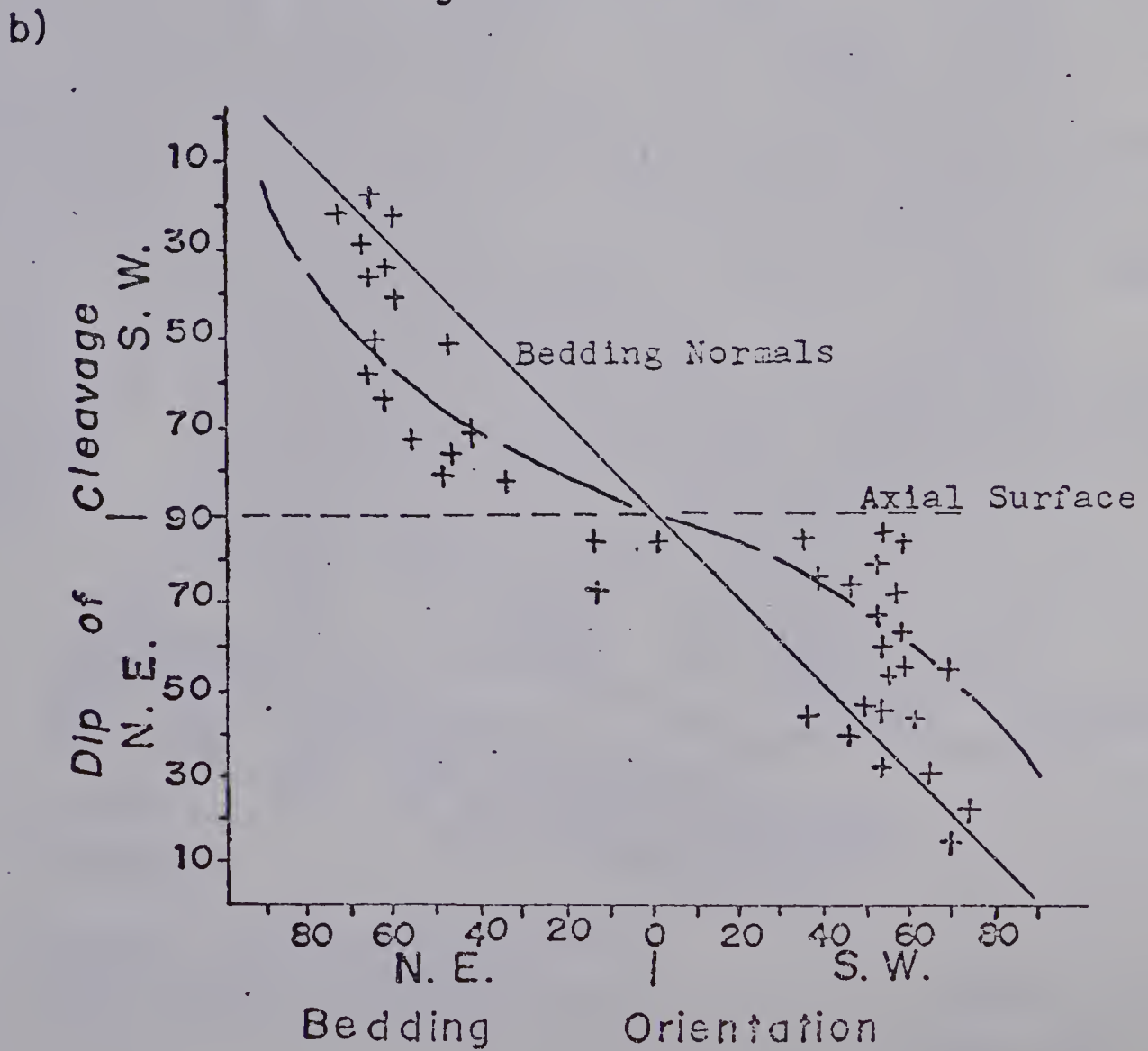
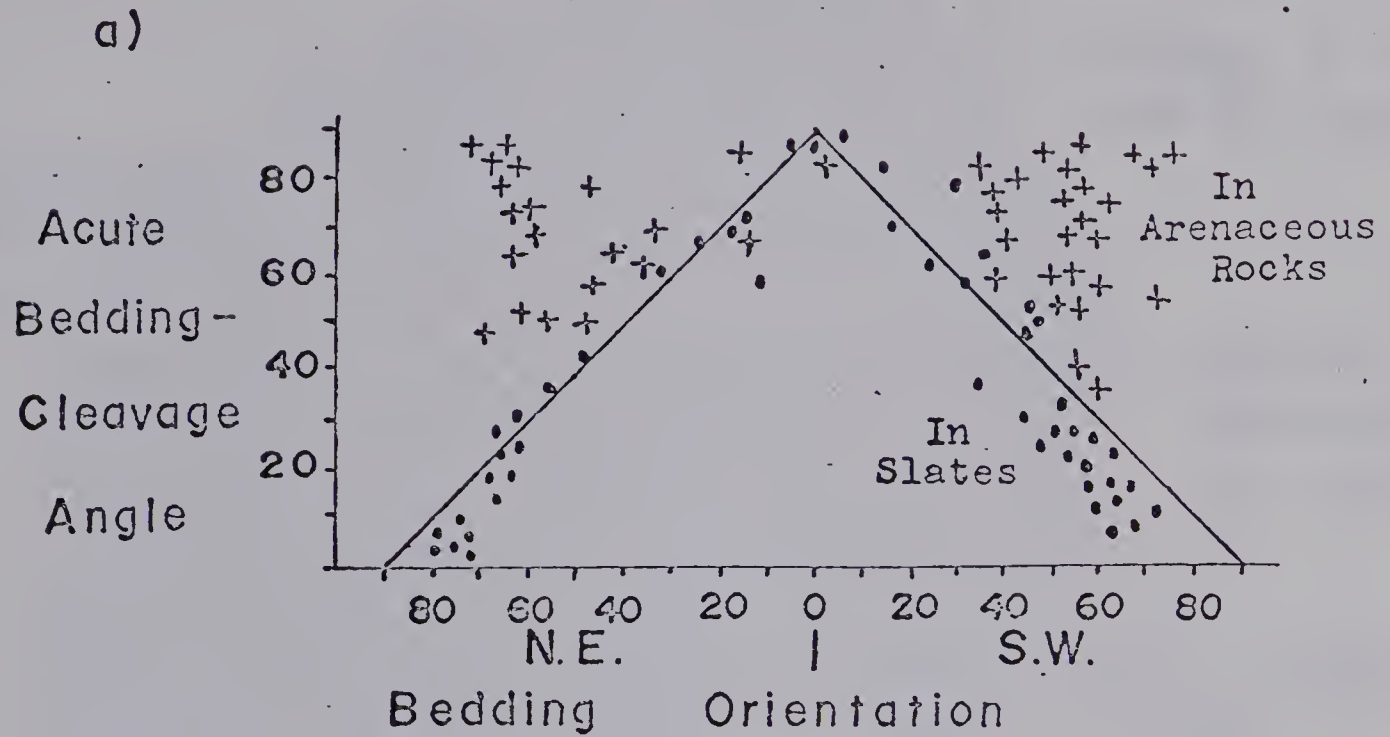
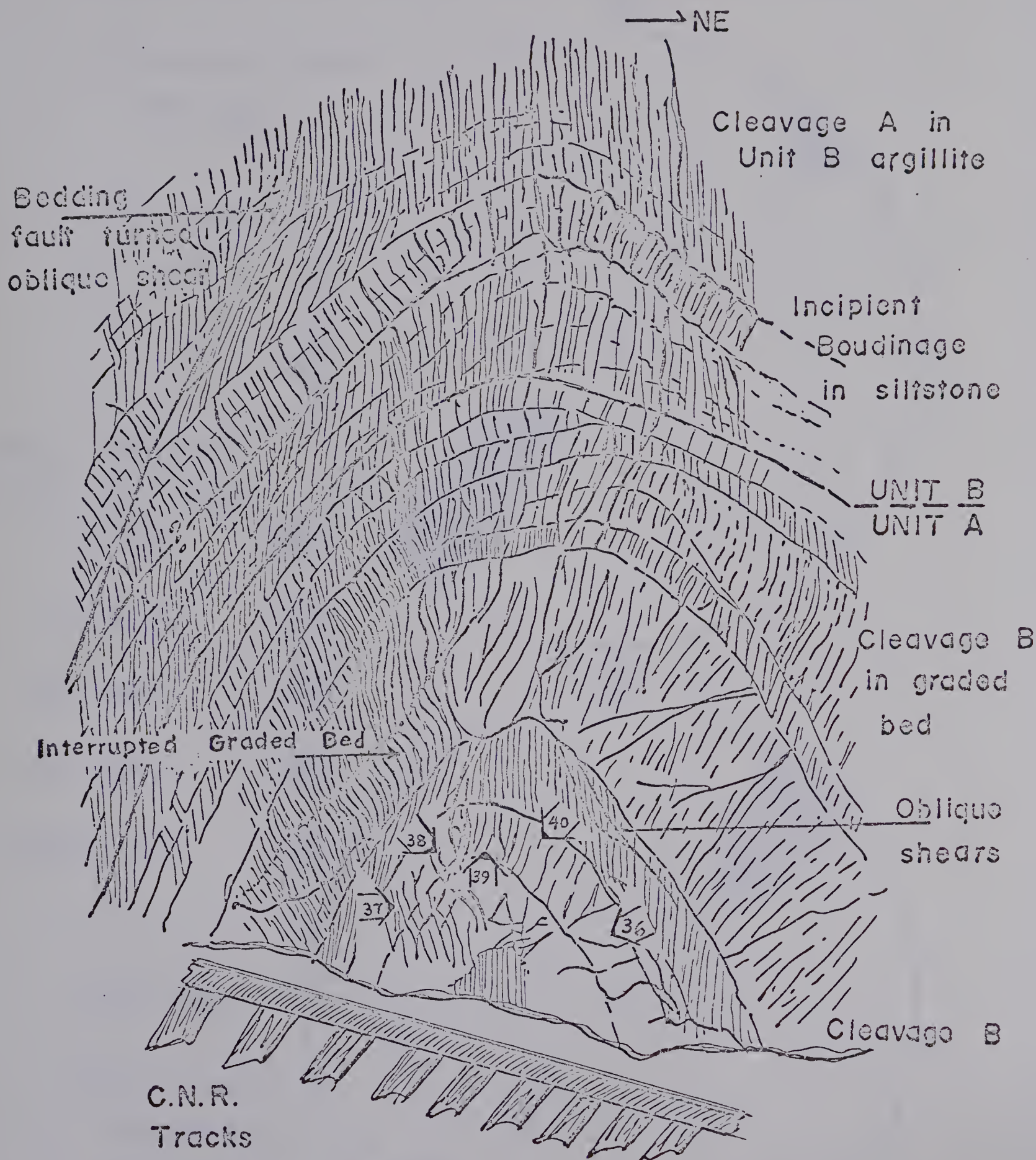




FIGURE 36: Core portion, Miette River fold.



Numbers (36, 37, etc.) indicate sites sampled for quartz deformation lamellae studies.

Scale  
0 5  
Foot —



FIGURE 37 Cleavage in the Miette River fold.

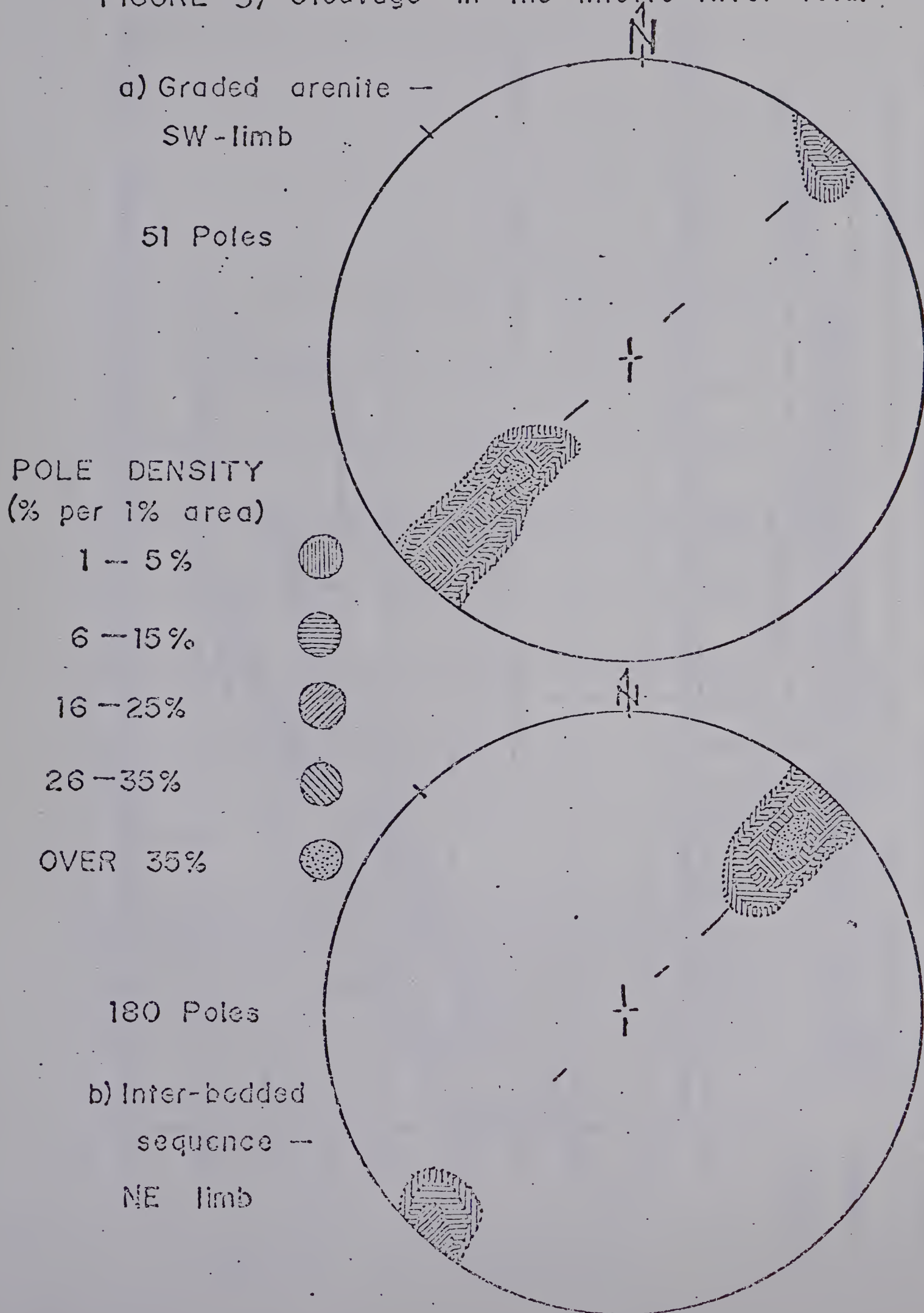
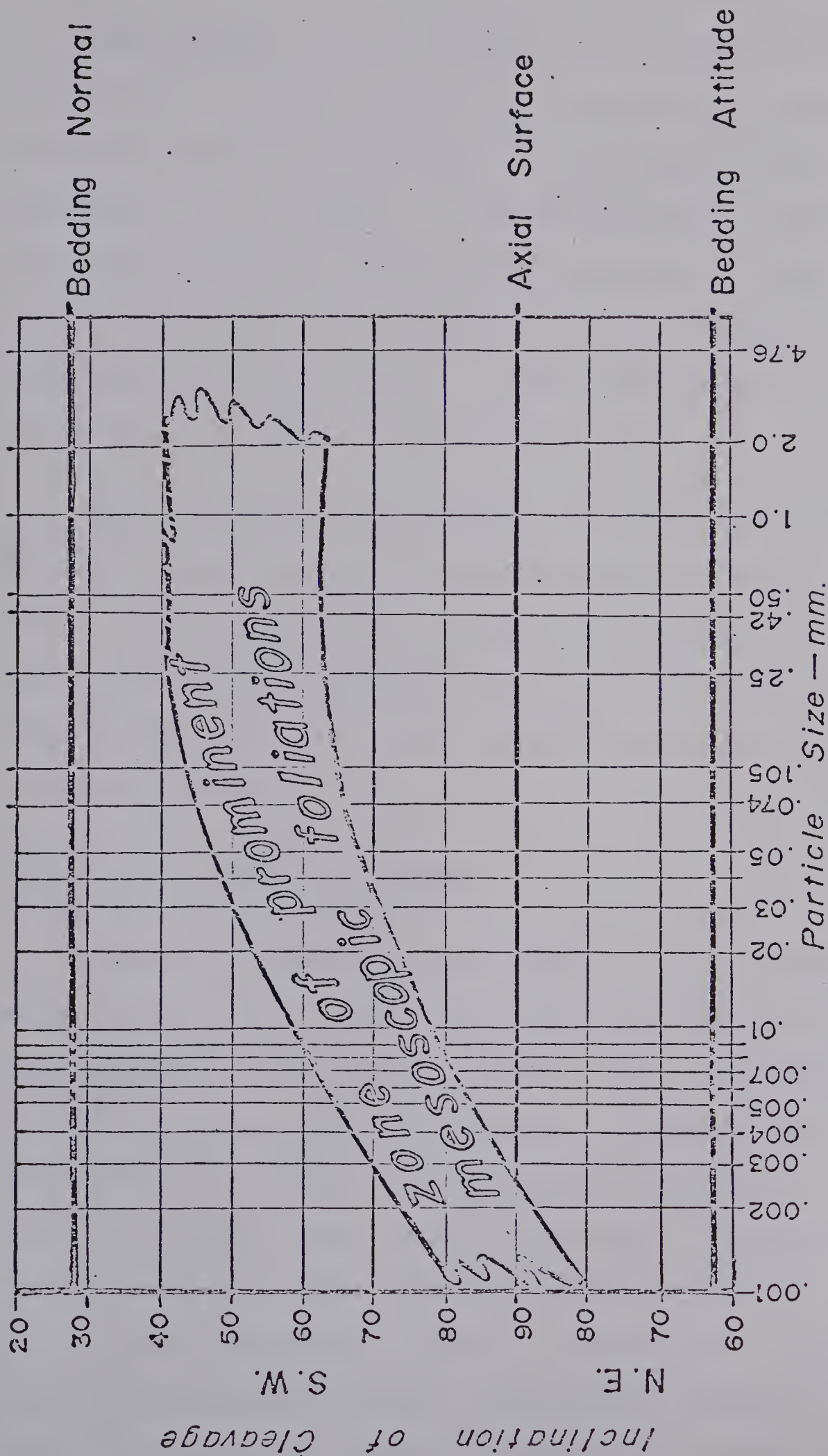




FIGURE 38



Clay	Silt			Sand			Pebbles
	V. Fine	Fine	Medium	Coarse	V. Fine	Coarse	
L.0039	.0039-	.0078	.0156-	.0312-	.0625-	.125-2.5	2.0 - 64.0

Based on 180 field observations in thinly-bedded 9.5 foot interval at top of Unit A, northeast limb Mierette River anticline.



### Gashes and Fractures

Also visible in the vicinity of the parasitic folds, but present elsewhere in Unit C, are numerous sub-parallel fractures which lie sub-normal to bedding and cut Cleavage B at low angles. The most prominent fractures are very long, slightly fanned and discontinuous breaks originating just above the base of Unit C along the basal detachment described above. These pass upward for some 15-20 feet into Unit C before dying out.

Short, quartz-filled gashes, with much the same attitude as the cracks, occur further down limb in Unit C. These structures are generally about one foot long and march en echelon to about as high above the base of Unit C as the longer features mentioned in the preceding paragraph.

### Deformation Lamellae in Quartz

Nearly all detrital quartz grains in the arenaceous units of the Miette River fold show some sign of having been strained. Most grains contain lines of liquid inclusions, many contain deformation lamellae, some are fractured. Rare recrystallized grains, when present, are clear, minute, unstrained individuals. Ruptured grains consist of parts with distinctly different orientation separated by planar or curvilinear fractures sub-parallel to the c-axis. Lamellae and trains of liquid inclusions generally trend approximately at right angles to these surfaces, as they do throughout the Jasper area.



As many as two or more systems of inclusions may occur in a single grain, but generally only one set of lamellae is present. In many grains lamellae are paralleled by lines of sub-microscopic inclusions of dusty appearance. All three of the lamellae types recognized by Carter and Friedman (1965) are present, the gradational or intermediate type being much more common than either the sharp or 'decorated' types.

#### Data Processing:

The orientation of lamellae is easily measured with a microscope equipped with a 4 or 5-axis Universal stage since the chosen lamella need only be rotated into parallelism with the 'east-west' cross-hair and the stage tilted about the 'east-west' axis until the structure becomes most sharply defined. In this study, however, the poles were not plotted immediately; instead, the scale readings were recorded and later converted to strike and dip in terms of reference co-ordinates. The converted readings were then punched on IBM cards and processed by computer. The resulting orientation diagrams are shown in Figure 39; each thin-section is shown separately. Synoptic diagrams showing rotated maxima referred to both



the horizontal plane and to a vertical plane normal to the fold axis are give in Figure 40\*. All diagrams are equal-area projection.

### Results:

Figure 39 shows the poles to about 2000 sets of quartz deformation lamellae from one of several beds sampled. The orientation of bedding and cleavage as measured mesoscopically for each oriented specimen are shown in Figure 40.

The most obvious correlations are those between poles to lamellae and bedding in the projections normal to the fold axis, and between lamellae poles and the fold axis as seen in horizontal projection.

### Kinematic Extrapolation

In accordance with the Sander philosophy, if the sequence of movements can be established for this simple fold, then a powerful interpretative tool may make itself available for our use in other parts of the area. One

-----

\* A rotation program to convert the readings from several thin-sections into a single set of data referred to the same reference plane was developed by the writer. However, subsequent testing of the computer program revealed an error in programming which caused a small percentage of poles to be plotted in the wrong quadrant of the projection. Although the program was corrected it has not been fully tested as yet; therefore none of the machine-rotated diagrams are included here.

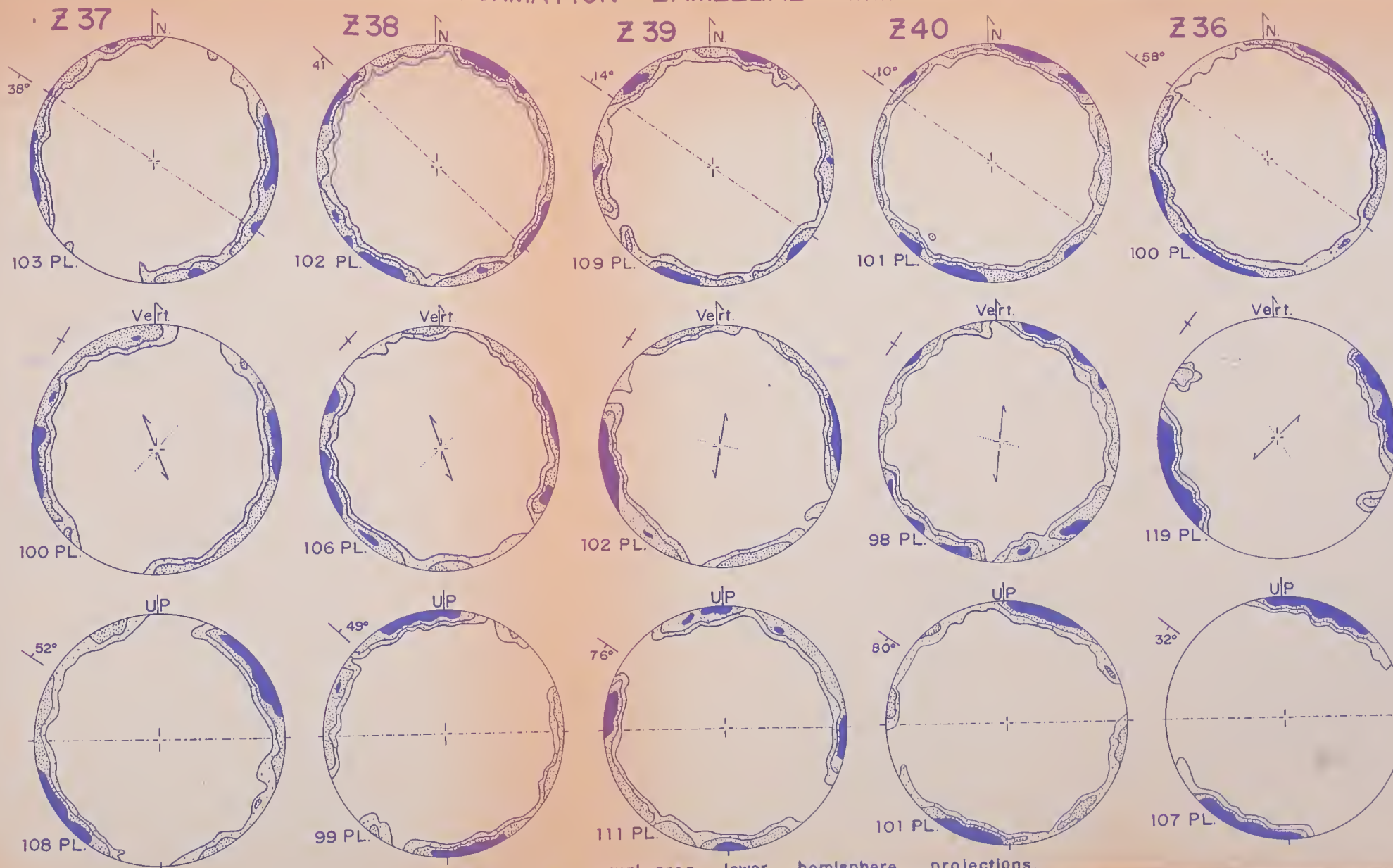


possible approach involves initial comparison of the various sub-fabrics, followed by an attempt to reconstruct the hierarchy of events; for the sake of brevity, these two steps will be partially combined.

First of all, the orientations of mean lamellae appear to reflect the influence of both cleavage and folding upon the internal fabric of the conglomerates. In the projections normal to the fold axis, paired maxima usually lie within  $5-40^{\circ}$  of bedding and another pair within  $10-45^{\circ}$  of cleavage, with at least one good maximum always within  $35^{\circ}$  of cleavage. In the horizontal projections, correlation between poles to lamellae and the fold axis is fairly consistent. In general the results accord fairly well with the observed fabric of the folded rocks and are similar to data reported by other investigators (see Scott et al, 1965, p. 741 ff for brief resume). Imperfections in correlation suggests that lamellae may have stopped forming before folding was completed. The strongest deviations occur in samples from the axial region of the fold (Z38-40). This agrees with the earlier remarks under sutured contacts where a strong correlation was shown to exist between the long axes of quartz and the local cleavage planes. It is likely that grain rotations accompanying the development of cleavage and, perhaps, fold tightening have affected the present orientation of the quartz lamellae.

Cleavage in the arenaceous units depends in nature





/ x Indicates orientation of projection plane and of corresponding thin-section

----- Bedding/cleavage intersection

∧ Cleavage trace ⊥ to the fold axis

..... Bedding trace ⊥ to the fold axis

**SAMPLE LOCATIONS**  
 Z37,38 Southwest limb  
 Z39,40 Axial region  
 Z36 Northeast limb

**LEGEND**

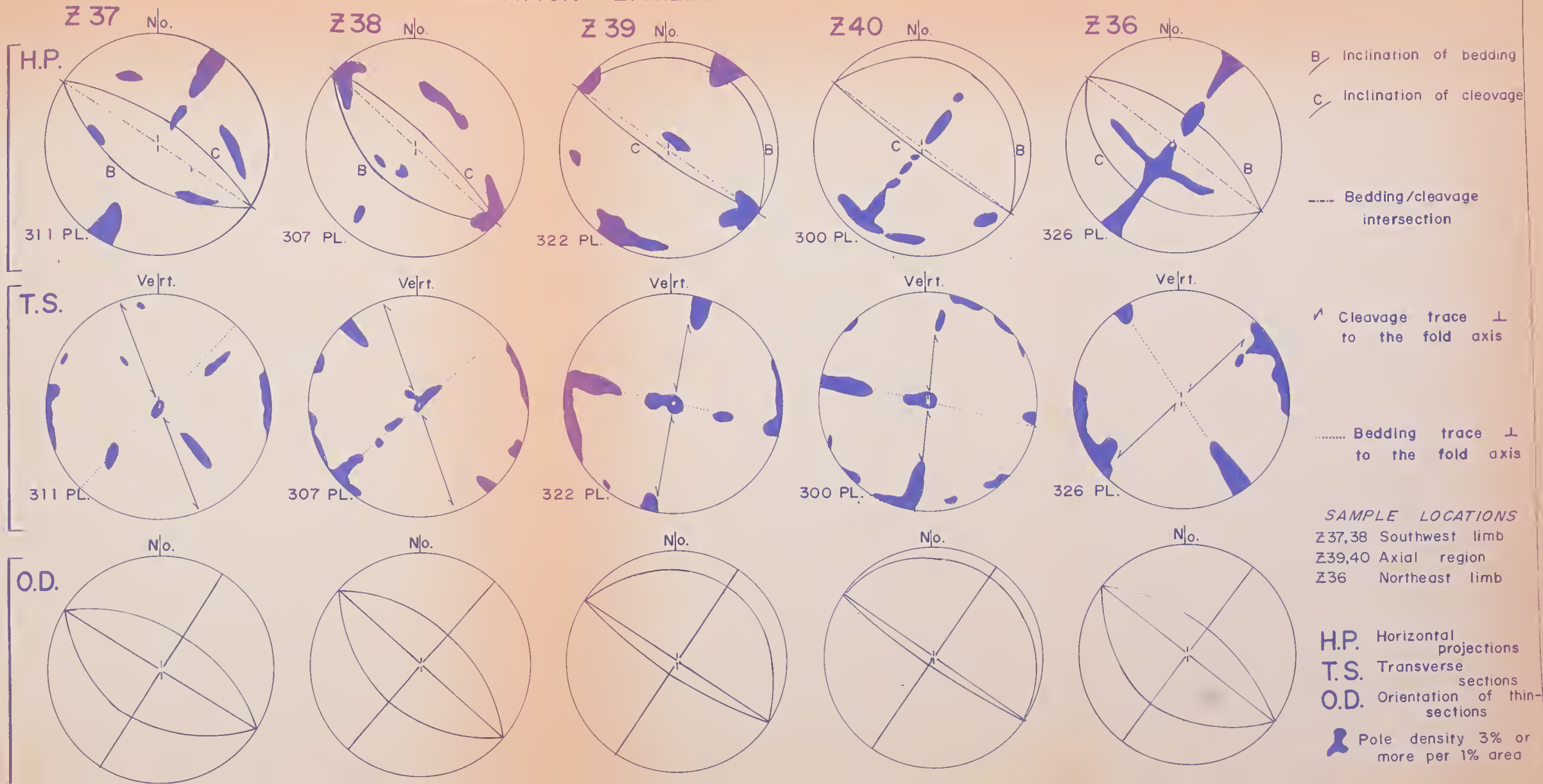
- 10% or more
- ▨ 5-10%
- ▤ 2-5%
- Less than 2%

All diagrams are equal-area lower hemisphere projections.



# QUARTZ DEFORMATION LAMELLAE—MIETTE RIVER FOLD

FIGURE 40





and orientation on the maximum particle size, on the degree of textural homogeneity, and on the structural position. First of all, increasing textural homogeneity (decreasing grain size in graded beds) would tend to produce shorter individual  $S_B$  trend paths (Figure 26, and earlier discussion). In effect, closer packing of grains will result; deflections of cleavage planes become more frequent, thereby reducing the angular momentum so that cleavage planes become gradually more regular, closer together, and nearer to parallel in orientation. Where graded bedding occurs, the presence of sigmoidal domains systematically decreasing in size and stacked in en echelon arrays will of necessity produce curved cleavage planes. Either buckle fold or shear fold movements will tend to flatten the sigmoidal domains and steepen the cleavage planes (reduce the acute bedding/cleavage angle).

Cleavage in the slates approximates an axial plane orientation. However, there are several indications of movements subsequent to cleavage development: a) occasional slickensides; b) micro-suturing along cemented contacts; c) low-angle cross-fracturing or shearing ( $S_{3A}$ ) related to  $S_C$  in the overlying arenaceous beds. One effect of such movements about parallel to cleavage would be to cause an apparent steepening of bedding (decrease of the bedding/cleavage angle) on the fold limbs. The observed 'roughness' of bedding surfaces suggests that translation parallel to cleavage may not have been equally distributed along the



limbs.

The observed dovetailed sutures resulting from the penetration of slaty material into overlying arenaceous beds along  $S_{2A}$  planes which pass upwards into  $S_B$  in the latter, suggest that Cleavage A (i.e.  $S_{1A}$  and  $S_{2A}$ ) pre-dates  $S_B$ . But both  $S_A$  and  $S_B$  consist of micaceous zones and inter-cleavage domains, and Cleavage B in graded beds passes back into Cleavage A, thus suggesting that  $S_A$  and  $S_B$  are also related in time and origin. The continuity of  $S_{3A}$  with  $S_C$  of the arenites, together with the cross-cutting relations these structures show with  $S_A$  and  $S_B$  surfaces indicates that they formed later than the latter, though not before folding was completed.

Other movements occurred locally during folding. There are bedding plane slickensides in Unit A and at the top of Unit B slates. In the case of the latter, slickensides are not visible near the parasitic folds which occur in a similar stratigraphic position further up-limb. It seems reasonable that inter-stratal slip between the two units may have been locally curtailed by increased frictional effects due to contact welding in the area where the folds now occur. Such resistance to slip may have forced a longitudinal crumpling of the slate and promoted development of the splayed thrust or decollement structure above the region of parasitic folds. Tension features lying about normal to bedding and cutting



Cleavage B at low angles also overlies this region. Cleavage A of the underlying slates dies out just below these folds, however, and therefore the temptation to label these structures as penecontemporaneous is strong indeed.

The presence of slickensides sub-normal to the fold axis on some ac joints suggests that the joints formed while folding movements were still going on.

The 'oblique-shears' or near-bedding faults at the core of the fold cut all other S-surfaces, but they could have formed after folding movements were essentially complete.

#### Dynamic Extrapolations

The presence of deformation lamellae at low angles to bedding can safely be taken to indicate that at the time of lamella formation these lower Wynd sandstones were capable of actively transmitting stresses parallel to bedding. Furthermore, the very presence of lamellae indicates that the quartz in these arenaceous units was at that time behaving plastically. Local variation in the direction of the maximum principal stress ( $\sigma_1$ ) application must have occurred between the time lamellae began to form and the end of folding giving rise to the observed discrepancies in fabric. If the 'normal' diagrams ('ac' fabric plane projections) are matched according to their



probable position during folding, then their 'a' axes approximately parallel the probable  $\sigma_1$  stress trajectories for a competent bed during folding (see Weiner, 1966, Figure 39). In Weiner's model, the fold limbs dip about 15-20 degrees whereas the limbs of the Miette Fold now dip at 45-50 degrees. However, lamellae bearing grains have suffered both active and passive rotation since the cessation of lamellae development.

In the light of the kinematic reconstruction given in the preceding section, it seems reasonable to suppose that Cleavage A was developing in the slates while plastic deformation was occurring in the arenites. It has been suggested (Charlesworth et al, 1967, p. 40) that  $\sigma_1$  of the orogenic stress system was sub-horizontal in the lower Wynd Formation. The same writers (op. cit., p. 42) have suggested that Cleavage A developed at right angles to  $\sigma_1$ .

The presence of laminar structure in Miette Group slates suggests that these beds were fairly well compacted at the onset of deformation. Because of their fine particle constitution the specific surface area per unit volume would have been very high so that frictional forces parallel to bedding would have been very high, though perhaps reduced by pore pressures. Because the slaty cleavage of the Jasper area possesses 2 partial fabrics (mica 'lining' along cleavage with lenticles of matrix between cleavage planes) and because it shows

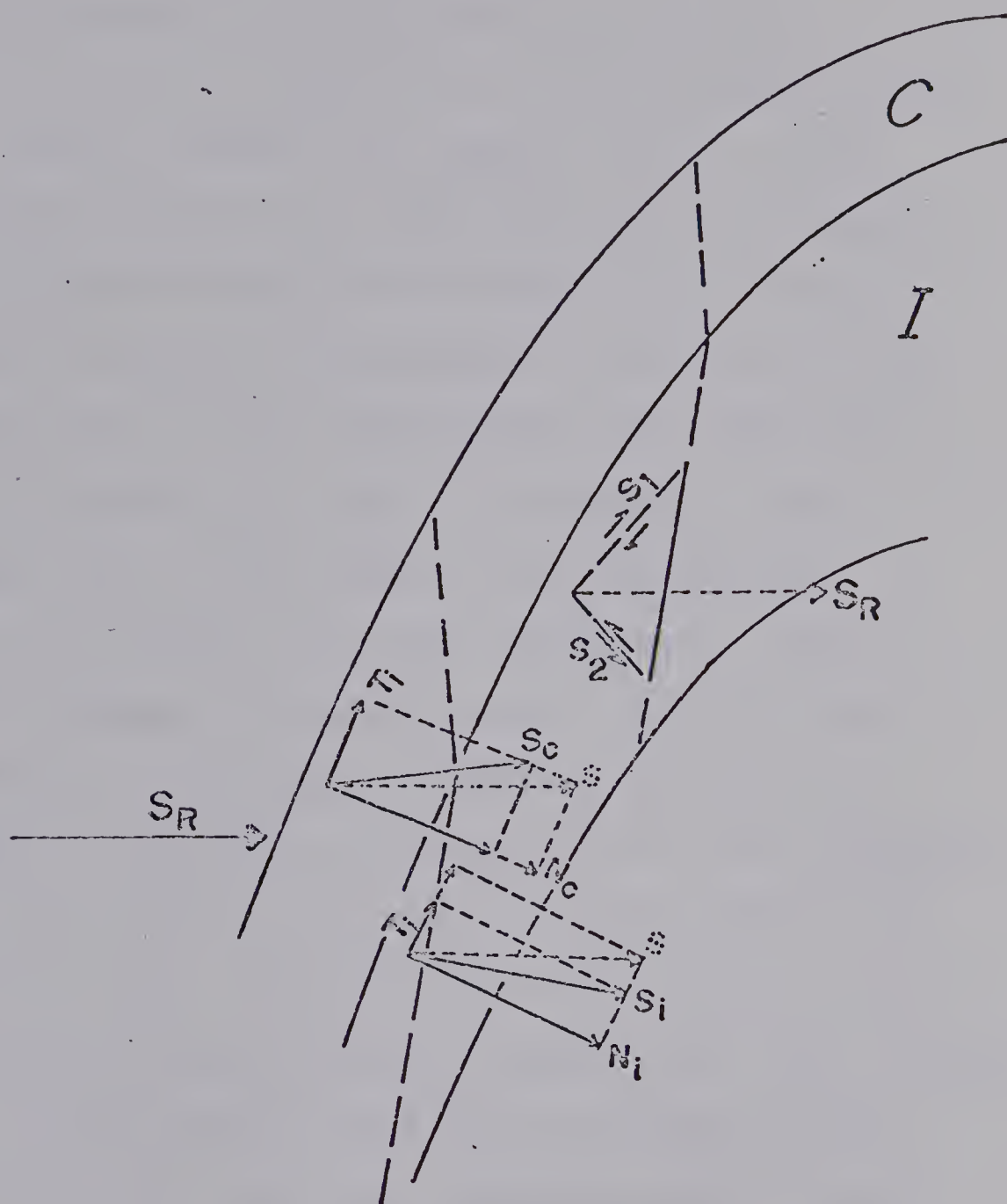


gradational relationships with other types of cleavage, it is unlikely that the Recrystallization Hypothesis is applicable. If we assume that micaceous and other particles in the undeformed slates had the shape of oblate spheroids which were mechanically rotated into parallelism with slaty cleavage planes during folding we can perhaps present a stronger case. At the onset of deformation, any ellipsoids whose unique axis lay at a high angle to the theoretical shear planes in the deforming rocks would have tended to rotate very slowly, while those whose short axis lay at increasingly lower angles to these 'flow' planes would accelerate and rotate more and more rapidly, (Ramsey, 1967, p. 221ff, especially Figure 5-46). Now, presumably, one of the maximum shear planes would have been at a low angle to bedding and the other at a high angle to it prior to folding. With initial flexuring of the beds the first of these, being the favored shearing direction, would have been rotated towards the  $\sigma_3$  stress trajectory---that is, towards parallelism with the axial surfaces of the growing 'trigger' folds.

Once flexures began to form other factors became increasingly more important. Local stress distributions, for example. First of all, there would be contact effects between different lithologies (Figure 41). An applied force ( $S_R$ ) can be resolved into tangential (T) and normal (N) components. In a relatively more competent material (C) much of T is taken up by elastic strain parallel to



FIGURE 4.1. Stress decomposition at lithologic boundaries.



$C$  = Relatively competent bed

$I$  = Relatively incompetent bed

$S_R$  = Regional stress

$T_C, T_I$  = Tangential component of  $S_R$

$N_C, N_I$  = Normal component of  $S_R$

$S$  = Resultant stress ignoring competency

$S_1, S_2$  = Theoretical planes of maximum shear



bedding, while part of N will be transmitted to the surrounding less competent bed (I) in which a plastic type of deformation is taking place. Since the effectiveness of N is reduced in C, the resultant stress ( $S_C$ ) is slightly rotated with respect to  $S_R$ . In the less competent bed more N is available but T is reduced so that  $S_I$  appears rotated in the opposite direction. The resultant stresses are therefore 'refracted' at the bedding interface. When interstratal slip takes place,  $S_R$  will be eccentric in I and the 'northeast' shear plane (upper part of the figure) will predominate. In C, plastic flow could take place during early stages of folding; accordingly one set of quartz lamellae would tend to form at a low angle to bedding, another at a higher angle. Initiation of plastic flow in the competent beds marks the beginning of new penetrative deformation in the slates ( $S_{2A}$ ). By this time slaty cleavage would be well developed and would closely parallel the axial surfaces of folds, though possibly cleavage development lagged behind the folding. Any more competent material interbedded with the slates begins to deform by plastic flow. Micro-bending would occur in thin competent laminae, the shape and orientation of the micro-folds depending on the main stress system. As compression continues, the shorter limbs of the microfolds rotate, gradually becoming parallel and attenuating until finally a new set of cleavage surfaces forms essentially parallel to the axial plane of the main folding. Actual slip may occur along



these new S-planes or 'slip' may be taken up instead by differential flow within the 'new' inter-cleavage domains. Where slates are more homogeneous, micro-bending of bedding does not occur; instead, the 'new' cleavage planes form where the 'old' inter-cleavage domains are more highly strained, stretched and sheared. Under other conditions, perhaps where conditions continue to favor plastic yield (lower Wynd strata?), slaty cleavage planes themselves may suffer micro-bending.

All of these movements will, of course, result in overall 'shortening' normal to the maximum principal stress and therefore volume requirements will have to be satisfied by extension in a direction parallel to the axial surfaces of folds. Therefore, as the fold limbs tighten, buckling movements in competent beds and inter-stratal slip between units begin to give way to shearing, probably first in the axial regions of similarly styled folds where volume requirements have become acute. As the fold continues to tighten, new shearing planes come into play down the limbs of the competent members. Because there are many large competent particles in Wynd sandstones, cleavage planes here will be further apart and irregularly spaced, unlike cleavage in the slates. Again referring to Ramsay (1967, p.223, Figure 5-46) we find that particles whose shape approaches that of prolate ellipsoids will rotate with rapid though decelerating motion if their unique axis lies at high angles to a shear plane, but if the unique axis is at a low angle to



such a plane the particles will rotate more slowly. Prolate particles will tend to produce a linear rather than a planar fabric, but once again the longer dimensions of particles will tend to parallel cleavage.\* Since the competent bed is still capable of transmitting a good deal of stress by way of contacts between coherent particles, the rest position of cleavage planes will be at a higher angle to bedding than it is in slates. Other reasons might also include: 1) the lingering effects of initial stress refraction in the competent bed; and 2) eccentricity of the compression due to movement parallel to cleavage in surrounding, less competent beds.

At still later stages in the folding, once the fold limbs become very tight, further 'shortening' normal to the tectonic stress can only occur by lengthening of the fold limbs. This takes place by: cross-foliation oblique to tectonic stresses, oblique shears and shears at high angles to bedding, and jointing. All are indicative of brittle rupture. Laminar-glide parallel to slaty cleavage plus external rotation would produce kink-folds in slaty cleavage and related parasitic folds on which incipient 'normal micro-faults' could develop. External rotation might also cause some movement along joints, offsets on oblique shears, and would bring boudins and block mullions into dimensional alignment with adjacent slaty cleavage planes.

-----  
\* If initial dispersion was random, then the degree of linear or planar fabric development is a function of: 1) the ratio of the length of the unique axis to the length of the remaining axes; 2) the amount of shear. Symmetry of the 'new' fabric depends on local 'flow' axes.



## Kinematics of Deformation in the Pyramid

### Thrust Sheet

Presumably, both the Old Fort Point and Wynd Formations were southwesterly dipping when deformation started, and later yielded by open to tight folding, by shearing, and thrust faulting during a period of regional deformation and metamorphism. The stratigraphically younger Wynd Formation has suffered somewhat less metamorphism than Old Fort Point strata.

Bedding has not been destroyed by either metamorphism or deformation, but several types of cleavage have developed. The most important of these are the cleavages marked by the parallel alignment of inequidimensional mineral grains; they are best developed in fine-grained rocks, principally in slates.

#### The Movement Picture in Slates

It may generally be stated that the increase in degree of metamorphism with age is accompanied not only by changes in style of folding but by changes in the character of Cleavage A as well. Thus in slates of the lower Wynd Formation Cleavage A:

- 1) Is defined by preferred mineral orientation and separates laminar domains;



- 2) Tends to parallel the axial planes of folds, but may deviate slightly from this orientation in the vicinity of coarser siliceous material, near faults, or even in the axial regions of some folds;
- 3) May itself be separated at intervals by parallel zones consisting of very narrow inter-cleavage domains separated by micaceous material.
- 4) May be further separated by an incipient, usually less steeply dipping, cross-foliation, the development of which was accompanied by crenulation of original slaty cleavage and a dextral shearing, viewed looking northwest;
- 5) Or, may be interrupted at intervals by a less steeply dipping set of shears at small angles to either the original slaty cleavage or its broader spaced variation without folding of the older cleavage planes; the type is especially common in the axial regions of folds.

In Old Fort Point strata the overall picture is similar but tighter folding and greater variation in fold orientation are accompanied by variations in Cleavage A:

- 1) Cleavage A may depart from an axial plane orientation where units are thin or lack homogeneity; it may approach parallelism with fold limbs in small, tight folds.
- 2) Cleavage A planes separate laminar domains defined by preferred mineral orientation, but Cleavage A fabric may itself be separated at intervals by zones of more intense strain along which shearing may or may not have taken place.
- 3) Cleavage A may show signs of shearing (slip) movements directed mainly along and parallel to cleavage surfaces with little or no deformation or inter-cleavage material.
- 4) Rock movements may also be traced through signs of 'flow' within the close-spaced slices, though the flow in adjacent layers is not always the same in magnitude or direction.
- 5) Kink-folds and incipient normal faults may be superimposed on Cleavage A fabric.



Cleavage A appears to be genetically related to cleavage and fracturing in more competent surrounding strata, such as quartzite and limestone.

#### The Movement Picture in Limestones

In handspecimen, Old Fort Point limestones occasionally appear undeformed even though internally they are so highly deformed that carbonate crystals in thin sections are extremely elongated and may be finely twinned. Occasionally intricate flow folds are encountered in rocks which have been visibly deformed by either Cleavages D or E to produce patterns of crumpled and offset slate and limestone. In the case of Cleavage E these features suggest deformation movements: initiated by flowage (glide and rotation), followed by the development of distinct zones of kinematic discontinuity along which displacements of varying degree and direction took place parallel to ( $S_E$ ) and oblique to ( $S_E'$ ) the axial surfaces of individual folds, and culminating in dilatation and change in shape in the axial portions of folds probably to the accompaniment of 'slicing' or mullioning once the limbs approach the isoclinal or overturned. Shearing movements are also commonly associated with Cleavage D, the orientation of which resembles that of Cleavage B. Even here a preferred orientation of crystals and 'flowage' structures is common, though the latter seems to have had little effect on development of cleavage.



## The Movement Picture in Arenites

Coarse-grained siliceous rocks present a much more enigmatic picture of the deformation history. In most thin sections a high per centage of grains are found to be inequidimensional; where cleavage is well developed, these inequant grains show strong optical and dimensional alignment. Inequant grains in many of the samples collected show strong consistency in shape as well: generally there is one long dimension, one intermediate, and one short. The ratio of the greatest dimension to the smallest ranges to more than 6:1, which is normal for quartzites in metamorphic terrains. The length difference between the smallest and intermediate dimension is rarely as marked. Both the longest and intermediate dimensions lie within a few degrees of being parallel to the foliation planes. Optic axes, themselves usually parallel to the longest axes of the grains, are often paralleled by undulatory extinction zones, and frequently by zones of recrystallization. Optical alignment of quartz in some thin sections is sometimes remarkably consistent, especially in samples from basal portions of well cleaved quartzites along sutured contacts with slates. Micaceous minerals, predominantly chlorite and muscovite lying in cleavage, usually lie tangent to the quartz grains of inter-cleavage domains. Composite quartz grains are occasionally present but the individuals of such composites do not appear to be elongated. In



addition to rotation, quartz grains reacted to deformative stresses by splintering along crystallographic directions. Thus, in the presence of Cleavage C optically continuous shards and splinters of quartz frequently lie in the cleavage plane together with the micas. Occasionally, Cleavage B and C planes which normally pass around quartz grains pass instead along clean breaks parallel to extinction zones in large quartz individuals.

Deformation lamellae are common in much of the quartz, the average lamellae ranging between symmetrical about cleavage to sub-normal to cleavage. Thus quartz also responded to tectonic forces by plastic deformation.

In Old Fort Point siltstones, as in the limestones, bedding has suffered crumpling.

#### Other Movements:

Bedding planes in both the Old Fort Point and Wynd Formations may be locally slickensided, the slickensides most commonly pitching about 90 degrees relative to the fold axes. Cleavage planes in slates may be slickensided as well and mineral 'streaking' is sometimes visible. Both types of movement produced local variations in the attitude of slaty cleavage and often 'bent' inter-cleavage domains to a flat-S shape. Movements due to shearing along Cleavage E in interbedded Old Fort Point limestones and slates has produced micro-folds internally and a crude block mullioning externally. Oblique shears of microscopic and mesoscopic sizes are more common in lowermost Wynd.



strata than in Old Fort Point beds; on the microscopic scale such shear planes cut cleavage planes at low angles while mesoscopically they tend to cut bedding at angles of less than 45 degrees although the ends of the shear zones, where visible, die out along existing cleavage. The direction of shearing and slip in all of the above is normal to the hinges of related folds, and the movements apparently took place along S-surfaces which existed at the time of shearing. Almost invariably these movements resulted in counterclockwise rotation of adjoining domains, a pattern of mass movement which is compatible with the regional pattern. However, deformation was not generally severe enough to completely destroy the axial regions of folds, nor was bedding obliterated. Thrust faults, which dip less steeply than bedding in overturned northeast limbs of folds but more steeply than Cleavage A, occur locally in the Old Fort Point Formation.

### Special Problems

#### Cleavage C in Rathlin Lake Synclinorium

The axial surface of Griffiths' (1962) syncline B is paralleled by Cleavage C. The plot of the acute angle between bedding and cleavage (Figure 14) shows that the acute angle increases systematically away from the axial region toward the limbs, as an ideal axial plane cleavage should. Griffiths therefore used the mean foliation plane



to define the axial surface of the syncline and attributed variations in the strike of cleavage and in the trend of the bedding/cleavage intersection to rotational movements on an inferred fault at slight depth below the axis of the fold. Since most folds in the lower Wynd Formation are upright we may therefore assume a tilting of 15 to 18 degrees counterclockwise. Setting the fold upright on the assumption that such rotation was passive, we find that Cleavage C in the west limb inclines southwest away from the axial surface by 6 degrees or less while on the east limb it inclines at 6 degrees or less in the opposite sense. Since this fanning is not systematic it may be largely the result of operator error plus local effects of the rotation process. Irregularities of cleavage planes in arenites might easily vary by 5 degrees from place to place.

It is interesting to draw a comparison between Griffiths fold and the situation which Ramsay (1967, pp. 500-504) calls 'buckle folds with internal deformation by tangential longitudinal strain'. In Ramsay's Figure 9-20 are shown the effects on a surface, B, that intersects another surface A which is being folded cylindrically solely with internal deformation due to longitudinal strain so that fanning and curvature are imposed on surface B. The dihedral angle between the two surfaces on the intrados increases along both limbs toward the hinge zone, approaching 90 degrees in the latter position. If



Ramsay's figure is inverted and passively tilted 15 to 20 degrees, the intersections of surface B with the inner surface of the concentrically folded layer A reproduce an almost exact replica of Griffiths cross-section. In Griffiths' fold, however, the surface corresponding to B is Cleavage C, a shear surface.

Assuming that Cleavage C initially formed parallel to a vertical axial surface by dimensional orientation of grains as suggested above, and was then tilted by counter-clockwise movement on the underlying fault, the cleavage would then lie at an oblique angle to a near horizontal regional stress in lower Wynd strata (Charlesworth et al, 1967). Tilting would tend to increase longitudinal tension in the axial region, already under tension due to tightening of the fold, but would put the competent material in the core into compression. The axial region of the fold might therefore be forced to shear hingeward because confinement in the core would prevent 'reverse fault' action into that part of the fold. The rigid body feature of Ramsay's model would thereby be somewhat modified by discontinuous strain effects, largely controlled by the presence of Cleavage C.

#### Comparison of Cleavage C with Others

Cleavage  $S_{3A}$  as discussed under sutured contacts, it will be remembered, was related to  $S_{1A}$  and  $S_{2A}$ .  $S_{3A}$

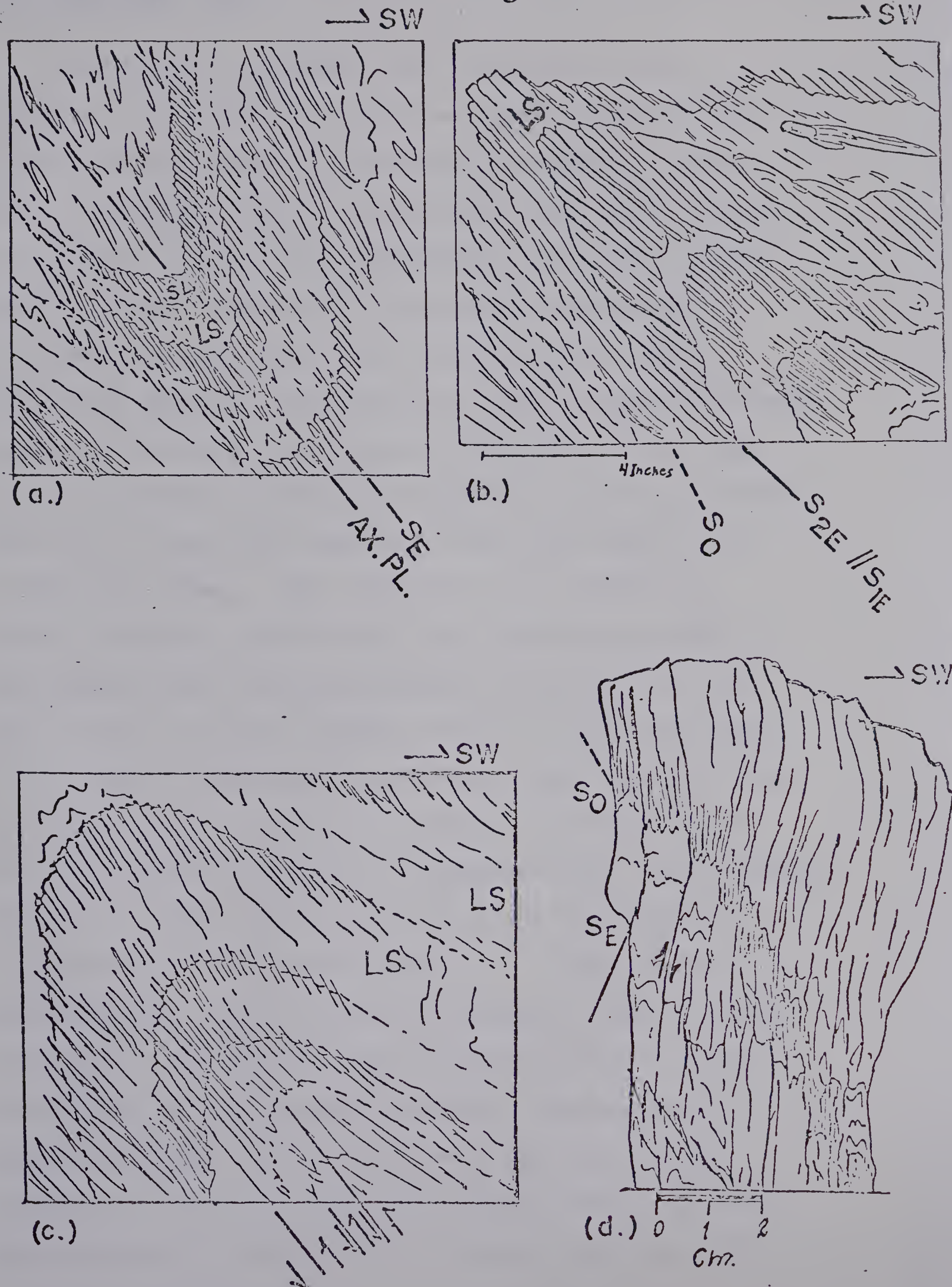


itself approximated an axial plane cleavage and developed by shearing. A replot of Evans' (1962) 'fracture' cleavage (Cleavage E) shows that most of the acute angles between bedding and cleavage lie in the 70 to 85 degree range regardless of the attitude of bedding, although there are deviations in both limbs (see Figure 19). This suggests that the attitude of Cleavage C in the Old Fort Point siltstones generally depends on that of bedding. Notice that while the acute angle between bedding and cleavage in the overturned northeast limb is essentially constant, it shows a tendency to decrease in inclination as the southwest limb is descended. The obvious explanation is that Cleavage E is essentially a late cross-foliation which developed shortly before folding movements ended, probably during overturning and tightening of the fold. The effect can be approximated with a deck of cards on which a moderately steep-limbed fold is drawn before cards near the middle of the deck are forced in the direction of the fold axis and a clockwise couple is applied to the whole thing.

The similarity of the fine structures accompanying Cleavage E to the modifications of Cleavage A which accompany  $S_3A$  suggests that Cleavages C and E in competent fairly homogeneous rocks are similar in development. In both cases the closer-spaced foliations are nearly contemporaneous with the coarse shear cleavage which truncates them. The major difference appears to be on



FIGURE 42 Kinematics in tight folds



Central zone, Meadow Creek anticlinorium.



the mesoscopic scale.

Though both Cleavages C and E are axial plane structures, Cleavage E in Old Fort Point limestones and slates tends to produce an incipient boudinage (Figure 41b, cf. Whitten, 1967, p. 305, figure 263 after Wilson). As a result of such block boudinaging the limbs of small folds in which Cleavage E is penetrative are almost invariably thinned while their axial regions, where stretching would be insignificant, tend to appear thickened because slippage has taken place along the slices. The result, as Weiner (1966, p.98) suggested closely resembles the slip or shear fold model of Turner and Weiss (1963, p. 481) and others. The crumpling of  $S_0$  between  $S_E$  planes, however, suggests that some shortening normal to  $S_E$  together with extension parallel to it by flow took place prior to actual slippage normal to the fold hinges. In the case of Cleavage E we therefore have much the same mechanism as that operating to produce Cleavage C, but the more homogeneous nature of limestones and silts promotes flow rather than shearing as in the more heterogenous conglomerates of the Wynd Formation. On that account Cleavage E is closer related to Cleavage A than it is to Cleavage C. Furthermore, this together with the earlier description of the gradation between Cleavages A and D suggests perhaps that at the time of deformation the competency of the fine-grained, thinly bedded limestones was intermediate between that of nearby slates and that of massive conglomerates.



Suggestions on the Mechanics of Deformation  
in the Pyramid Thrust Sheet

At least three general pronouncements apply:

1) in a given domain under given stress conditions, the type of deformation and the class of structures which develop will be a function of overall competency and lithological homogeneity; 2) local stresses and metamorphic conditions vary with time so that physical properties of rock types will also vary; 3) the structural and stratigraphic position relative to the orogenic stress system influences the physical conditions and the responses of the deforming rocks.

In the Jasper area, overall competency of the Miette Group rocks decreases with increasing age. The overall ductility of the Old Fort Point beds at the time of deformation was greater and the ductility contrasts between lithologies less marked than in Wynd strata. In the more homogeneous Old Fort Point strata cohesion across bedding was not great and bedding, therefore, played a subordinate role during folding. Weiner (1966, p. 147) suggested that temperatures during metamorphism were probably about  $300^{\circ}\text{C}$  and that water pressure equalled load pressure; at a depth of burial on the order of 25,000 - 35,000 feet the latter would be about 3000 bars. Presumably, entrapped water in the Old Fort Point Formation



would have been at somewhat higher pressure than that in the overlying, more permeable Wynd strata. If so, both shearing and compressive strengths of Old Fort Point rocks would have been significantly lower than normal. Since only about 5000 feet of section is involved, contrasts attributable to stratigraphic position may not have been marked. Nevertheless, it is reasonable to assume that both horizontal and vertical variations in the effectiveness of the applied tectonic stresses existed across the map area during deformation, and that shearing stresses were more effective with increasing depth.

Figure 43 is a 'Hafner' diagram (modified after Billings, 1954) which assumes: 1) that the deforming rocks are isotropic have a uniaxial compressive strength of  $3000 \text{ kg/cm}^2$  and behaved like elastic solids; 2) that the block being stressed is 10 miles wide. Superimposed on the standard state is a variable horizontal stress and a vertical shearing stress which increases with depth. At a depth of 30,000 feet the maximum principal stress trajectories plunge steeply to the left. However, the angle of plunge of  $\sigma_3$  decreases from right to left so that the axial surfaces of any folds which develop normal to the maximum stress would incline in a similar fashion. One of the two possible sets of faults would be sub-horizontal on the left side of the diagram, but these faults would 'climb' in the last 3 miles of section so that at the right margin they would have a dip of about 20 degrees 'west'. The



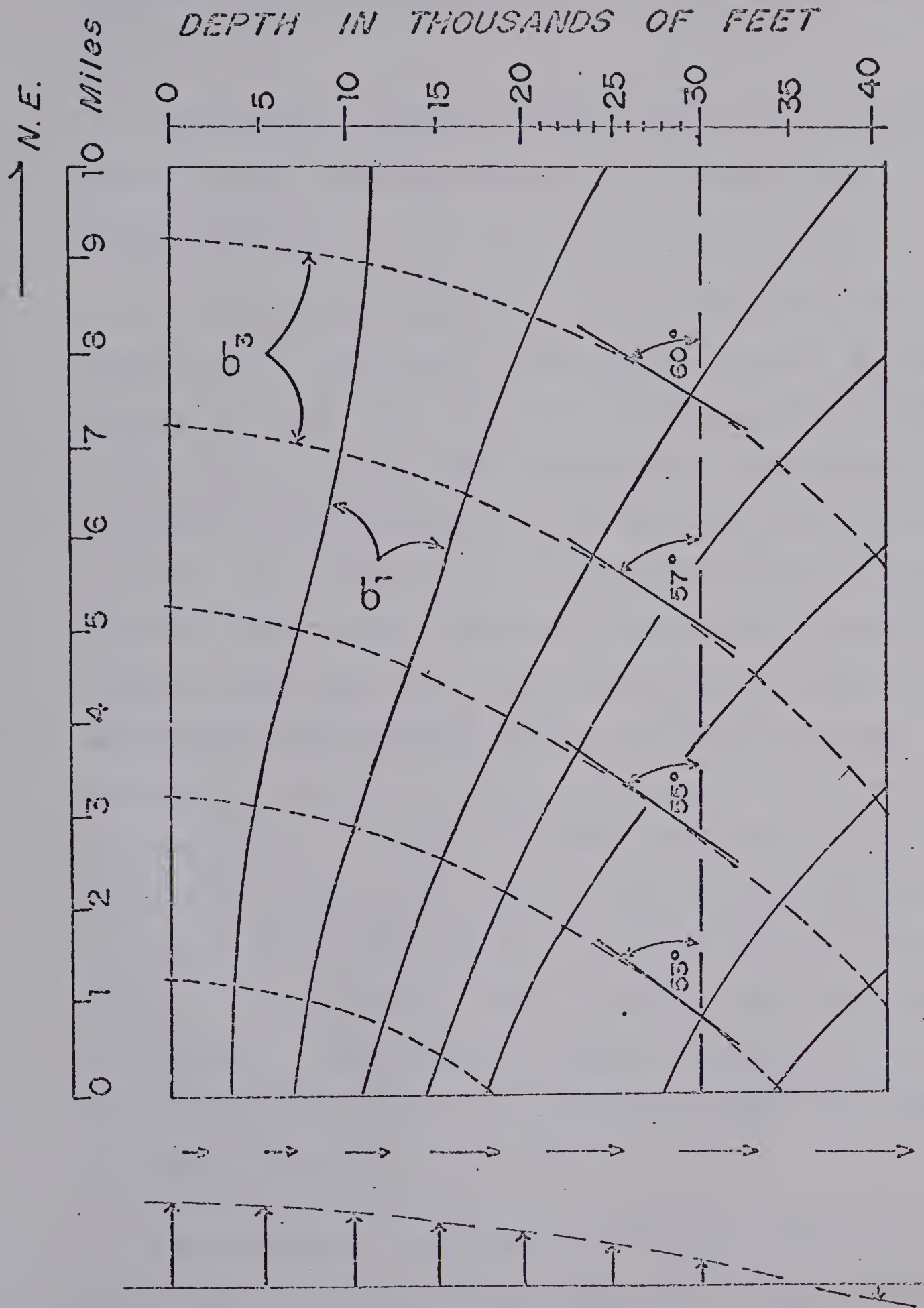


FIGURE 43. Stress analysis in an isotropic medium (see text). Additional stresses, necessary to preserve equilibrium in the block, are not shown.



complimentary set of faults would be of the high angle reverse type.

Slates have a rupture strength of 600-3130 kg/cm<sup>2</sup> under uniaxial compression and 150-250 kg/cm<sup>2</sup> under shearing stress.

If faulting is assumed to have accompanied the folding of Old Fort Point slates, then movement of the hanging wall material along the low dipping set of faults would tend to increase the inclination of the axial surfaces of folds developing near the right end of the section. The apical angle of such folds would be greater than for folds at the left end of the section because rotation could keep pace with folding on the right, and because the effectiveness of the horizontal stresses decreases towards the right. If we assume that hanging wall material at a depth of 30,000 feet moved along a fault plane dipping 20° 'west', then in order for material 7 miles from the left margin to move as far as the right margin, a stratigraphic throw of nearly 6000 feet would be required. Interestingly enough, this is about half the stratigraphic throw on the Pyramid Thrust just east of Jasper townsite.

The principal differences in the characteristics and probable kinematic significance of the various types of Cleavage developed in these rocks appears to be the result of changing conditions during deformation. Virtually



all of the observations are compatible with the idea of a nearly universal progression from penetrative to less penetrative types of structures with increasing time. Such discrepancies as exist are generally local, and are probably due to gradients in temperature and pressure, as well as to textural and compositional variations.

Internal deformation in rocks of the Wynd Formation, where the level of competency was higher, is most readily explained in terms of stresses associated with flexuring of the beds.

### CONCLUSIONS

In the Jasper area, mesoscopic folds in both the lower Wynd and Old Fort Point Formations occupy positions on the northwesterly trending anticlinoria and synclinoria which cross. The area; major and minor fold axes, bedding - cleavage intersections, and fault traces are generally concordant with regional structure, although mesoscopic folds of the lower Wynd formation are wider spaced and more nearly upright than those of the Old Fort Point Formation.

Folds in both units are inequant in shape, the competent beds in the lower Wynd Formation having folded



concentrically whereas bedding in the northeast limbs of Old Fort Point folds has undergone thinning.

Micro-tectonic detail, however, is somewhat more complex and variations depend on the host lithology, structural setting, and the modifying presence of other structures. Cleavage in slates ranges between 'slip cleavage', with prominent shearing effects, and 'flow cleavage', in which platy minerals throughout the mica-rich rock are parallel; thin section examination suggests that the principal difference between the two types is a function of grain size rather than of mechanics. Cleavage in more competent rocks is better explained in terms of stress couples arising during flexuring. Geometric and petrographic characteristics of the cleavage types found in the Jasper area are fairly uniform and commonly gradational, so that it seems unwarranted to presume different modes of origin. It is therefore concluded that all cleavages in the Jasper area are related to folding movements, axial plane 'slaty cleavage' having developed during the early phases of folding, axial plane 'fracture' and crenulation cleavages during later kinematic phases, and lastly inclined sets of cleavage developing when low grade metamorphic conditions were firmly established. The sequence of tectonic events may be summarized as follows:

- 1) Early folding phase

- (a) Initial flexuring of strata.



- (b) development of cleavage ( $S_{1A}$ ) in slates
- (c) plastic deformation in competent rocks;  
quartz deformation lamellae formed.
- (d) slip parallel to and between slaty cleavage  
planes ( $S_{2A}$ ); bedding planes completely  
passive in incompetent units.

2) Later kinematic phase

- (a) localized formation of early strain-slip  
Cleavage in slates ( $S_{3A}$ )
- (b) main strain-slip cleavage ( $S_{AB}$ ) and cleavage  
suturing.
- (c) development of 'fracture cleavage' ( $S_B$  and  $S_D$ )

3) Latest kinematic phase

- (a) localized formation of low-angle cross  
fractures ( $S_F$ )
- (b) Localized formation of late strain-slip  
cleavage ( $S_E$ ).
- (c) late 'fracture' cleavage ( $S_C$ )
- (d) jointing and other types of brittle rupture.

The above sequence suggests a progressive change in metamorphic conditions from initial folding of an essentially plastic rock mass, through plastic failure and finally brittle rupture.

Pumpelly's Rule, which not only implies the regular geometric relation between associated large and small



folds, but also the correspondence existing between stratification, cleavage and lineations within macroscopic domains, aptly defines the structural relations in the Jasper area.



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